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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

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FABRIC ANALYSIS OF SOME GREEK MARBLES AND ITS APPLICATIONS TO ARCHEOLOGY

L. E. WEISS

ABSTRACT. It is suggested that petrofabric analysis may assist in the restoration of fragmentary inscriptions and works of art made of marble. Petrofabric principles which may be of importance are discussed, and a method of preparing "fabric pictures" summarizing distinctive features of the fabric of individual specimens of marble is outlined. Seven specimens of marble from quarries in Greece are analyzed in this way, and it is concluded that distinctive fabric pictures will be obtained from most marbles. Procedure in applying these techniques to specific problems is demonstrated for hypothetical examples.

THE PROBLEM

In a recent paper Herz and Pritchett (1953) have demonstrated to students of Attic epigraphy the importance of describing specimens of marble in the systematic manner used by petrologists. Epigraphists, and most archeologists, use unsatisfactory petrographic terms to describe fragments of marble; and a definite locality of origin for individual specimens of marble is commonly assigned on the basis of a superficial examination of color and general appearance. Herz and Pritchett state that color alone is not a criterion of the place of origin of a marble; the quarries in Attica which they have examined show that there is a considerable variation in the color and texture of the marble within any one quarried mass. A more complete descriptive analysis using not only color but grain size, composition (accessory minerals present), and orientation of foliation[1] and lineation is suggested. Examination of these features in two or more fragments of marble in many instances will give sufficient information to enable one fragment to be related to another. By examining the orientation of linear structure in two specimens of marble previously supposed to have formed part of one stele, Herz and Pritchett successfully demonstrated that these fragments could not have formed part of one block of marble (1953, p. 81-83), thereby solving an archeological problem.

Careful study of immediately visible features of fragments of most marbles will indicate readily whether or not they are parts of one small block. Fragments with distinctive colors, accessory minerals or, in some instances, planar and axial structures almost always can be readily matched, both generally and, by careful use of vectorial data, with regard to their specific orientation[2] in relation to each other.

[1] Throughout this paper the term foliation applies to the most strongly developed planar structure visible in the marble, regardless of whether or not it represents sedimentary bedding.

[2] It should be noted that *orientation* refers to the attitude of a structure with respect to geographical or other directional coordinates; it should not be confused with *position* which defines a location.

It is the purpose of this paper to outline an extension of the method of descriptive analysis suggested by Herz and Pritchett to include the study of features of the microfabric of marble, such as the preferred orientation of the [0001]-axes of grains of calcite, which will either confirm a common origin of fragments already suggested by other features, or, what is more important, will enable fragments which show no recognizably distinct features to be compared and contrasted on a basis other than that of general appearance. It is with the techniques now to be described that the simplicity of the method vanishes. The principles and techniques involved cannot be applied except by an experienced worker with a knowledge of structural petrology. The interpretation of statistical diagrams for the preferred orientation of calcite requires specialized knowledge and considerable experience. It must be stated, therefore, that the time-consuming techniques now to be described should be applied only when simpler methods have proved unsatisfactory.

There are three main problems concerning the mutual relationship of fragments of carved or inscribed marble:

1. Are the fragments part of a block of marble quarried in one piece?
2. If so, what was the orientation of each fragment?
3. Is it possible to assign to a marble a definite locality of origin?

It is the purpose of this preliminary paper to discuss whether fabric analysis of marble will assist in solving these problems.

DISCUSSION OF PRINCIPLES INVOLVED

Petrofabric analysis of marble generally shows that the grains of calcite have a greater or lesser degree of preferred orientation of their [0001]-axes (*c*-crystallographic axes). An examination of the existing published diagrams for [0001]-axes shows that two main patterns of preferred orientation commonly occur and these grade one into the other:

1. An area or areas of high concentration at a high angle to the foliation (where present); for example, in Yule marble (Turner, 1949), and the Sonora marble (Turner, 1953);

2. An area or areas of high concentration at a high angle to the foliation spreading into a more or less distinct girdle the pole of which may be parallel to a visible lineation in the fabric; for example, in marbles from Tomintoul and Dulnain Bridge (McIntyre and Turner, 1953), and in marble from the Mojave Desert (Weiss, 1954).

The kinematic significance of these patterns in terms of rock flowage and mechanisms of gliding, twinning, and rotation of grains does not concern us here; only the general form of the common patterns of preferred orientation should be noted. That is, in marbles which are *S*-tectonites with foliation and no lineation (planar control of fabric) there is a tendency for [0001]-axes to lie at a high angle to the plane of foliation; whereas in marbles which are undoubted *B*-tectonites with marked lineation which may be paralleled by small-scale folds (axial control of fabric), [0001]-axes tend to lie in a girdle with one or more maxima normal to the lineation (*B*-axis).

Marble used for making stelai and for building may show either a planar or axial control of fabric to a high degree. Those used for sculpture tend to

have weak linear and planar structures as these are directions and planes of weakness in the fabric. The most sought-after marbles for this purpose will be the "freestone" varieties; that is, marbles which break with approximately equal ease in all directions. In such marbles preferred orientation of [0001]-axes will be correspondingly weak; however, as will be shown below by analysis of a fragment of Parian marble, statistical analysis shows that in even the most equigranular and megascopically isotropic marbles a distinct preferred orientation of the calcite lattice may be found.

The purpose of studying the preferred orientation of calcite in the present context is to decide whether or not the patterns obtained will define a direction or plane in the fabric which will be constant in orientation throughout a block of marble of a size suitable for a stele or a piece of sculpture. There are two features of the patterns of preferred orientation of [0001]-axes which may be important in this respect, namely, the area of maximum concentration and the girdle.

It has already been stated that the [0001]-maximum tends to be oriented at a high angle to the foliation. This angle can vary within one body of marble (Weiss, 1954, p. 36-37). How much it varies within a small block of marble the size of one stele will depend upon the tectonic style of the particular rock. For instance, if the foliation is regular and unfolded, then it is possible that the maximum of [0001]-axes will be inclined to the foliation at a constant angle (fig. 1-a). If, however, on the scale of the block under consideration, the foliation is folded, then, depending upon the type of fold, two simplified possibilities may be suggested (Sander, 1951):

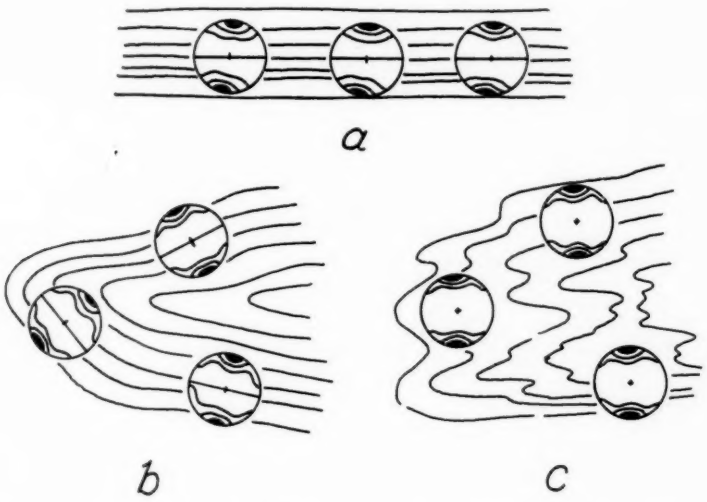

Fig. 1. Some possible relationships in orientation between [0001]-axis maxima and foliation in different marbles.

1. If the fold is capable of being "unrolled," that is, produced by rotation (flexure) of a fabric such as that illustrated by figure 1-a, then the [0001]-axis maximum will have a different orientation with reference to the coordinates of the block in different parts of the fold (fig. 1-b). Ideally, the angle between the maximum and the foliation should be constant.

2. If the fold is incapable of being "unrolled" (probably the common type of fold in marble which has suffered plastic flow), there may be an approach to direction-homogeneity of orientation of [0001]-axes (fig. 1-c).

From these considerations, it is concluded that a single maximum of [0001]-axes in a orientation diagram will not, by itself, define a direction which is likely to be constant throughout one worked block of marble. If a marble has direction-homogeneity of preferred orientation of [0001]-axes, then orienting a single maximum may be used to match fragments with a unique orientation determined by the presence of one inscribed surface, as of a stele. However, if matching of fragments is to be extended to initially large volumes of marble, such as single blocks from which a piece of statuary has been made, then a single [0001]-axis maximum will be insufficient to define a unique orientation for broken fragments even if the preferred orientation is uniform throughout the block. The maximum can define only one constant direction and not the sense of this direction.

The second feature of the patterns of preferred orientation of [0001]-axes is of more importance in the present context. Petrofabric analysis of marbles and other rocks has shown that *B*-axes, defined by the normals to planes of symmetry in the fabric, tend to assume, in strongly deformed rocks, regular orientations over large areas. It is reasonable to suppose that a *B*-axis, even if it is defined only by the girdle pattern of [0001]-axes, generally will be constant in orientation throughout a quarried block of a suitable size to be worked, and probably throughout one large quarry. The *B*-axis will, like the direction defined by a homogeneous preferred orientation [0001]-axis in a maximum, admit a twofold ambiguity in sense (fig. 2).

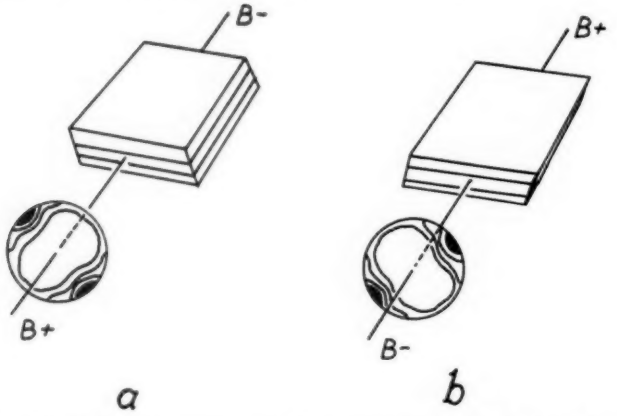

Fig. 2. Orientation diagrams viewed along opposite senses in the direction of the *B*-axis.

The maximum or maxima of [0001]-axes generally to be found around the periphery of girdles are subject to the same variation in orientation with respect to foliation and geographical coordinates as are the single maxima to be found in the orientation patterns prepared from fabrics with planar control.

It is to be concluded from these considerations that the preferred orientation of calcite considered alone will provide, in many instances, insufficient information to establish the relative orientation of fragments of marble where no other guide to orientation is present. It is necessary to seek other means of obtaining constant directions in the fabric of a block of marble. Such a means exists in the technique of dynamically interpreting {01$\bar{1}$2} twin lamellae in marbles with postkinematic crystallization first described by Turner (1953), and subsequently applied by McIntyre and Turner (1953), Weiss (1954), Gilmour and Carman (1954), and Clark (1954). The underlying principle is briefly as follows: if the {01$\bar{1}$2} twin lamellae in a marble have been produced by stress, then it is possible to construct for each grain two mutually perpendicular directions of applied stress (a compression and a tension) which would most readily account for the observed twins. If these directions are plotted for many twinned grains within one thin section and are found to lie in distinctly defined areas of the projection, then it is possible to say that either a compression or tension or both applied in the directions defined by the corresponding maximum concentrations of points could have produced the twinning visible in the marble.

In all marbles with extensive postkinematic crystallization in which the twinning has been studied in this way, either the points of compression or tension or both have been found to lie in distinct and usually strong maxima. This preferred orientation suggests that in marbles with postkinematic crystallization the twinning has been produced at a late stage in the history of the rock, generally after the preferred orientation of [0001]-axes has been acquired. A marble is defined here as showing postkinematic crystallization if the grains of calcite are clear and unstrained with no intense twinning on closely spaced {01$\bar{1}$2} planes, no bending of lamellae or undulose extinction, and no rotated relict twin lamellae indicating complete or nearly complete twinning of grains (Borg and Turner, 1953). Marbles with crystallization defined as pre- or parakinematic show some or all of these features as well as evidence of grain rotation during penetrative movement (Weiss, 1954). Points of compression and tension constructed for twinned grains in these marbles do not lie in simple distinct maxima but fall in coincident *ac*-girdles around the *B*-axis of rotation. These patterns are a result of an apparent rotation of stress axes around *B* caused by relative rotation of individual grains as they become twinned and retwinned during penetrative movement. This rotation destroys interlocking boundaries between grains and, in some marbles, produces granulation.

It is thus possible to distinguish marbles with dominantly postkinematic crystallization from these with dominantly prekinematic crystallization by

microscopic observation. This is important, for only marbles in which a weak stress at a late stage has affected a completely recrystallized fabric will have twin lamellae suitable for the construction of points of compression and tension. If this stress becomes too pronounced it will cause twinning upon $\{01\bar{1}2\}$-planes with low coefficients of resolved shearing stress, complete or nearly complete twinning upon $\{01\bar{1}2\}$-planes with high coefficients of resolved shearing stress, and, when the movements become truly penetrative, relative rotation of grains. All of these processes will tend to weaken and disperse the initially strong maxima of compression and tension points which it is possible to construct for very weakly developed twin lamellae in the marbles with a crystallization defined as postkinematic.

Several marbles which appear to have suffered postkinematic crystallization have already been analyzed, and it is known that in specific areas the orientation of constructed points of compression and tension may be constant throughout one hand specimen, in two hand specimens collected one foot apart (McIntyre and Turner, 1953, p. 234, figs. 5a and b), and even throughout one quarry (Gilmour and Carman, 1954, p. 58). It is likely that examination of the twin lamellae in fragments of one worked block of marble with postkinematic crystallization may make possible the recognition of one or two directions (preferred orientation of axes of compression and tension) which have a constant orientation within the block. The seven specimens of marble from Greece, the fabrics of which are described below, all show postkinematic crystallization, and, indeed, it is to be expected that most marbles chosen for their beauty will be of this kind. Marbles with prekinematic crystallization have uneven grain size and a correspondingly dingy appearance when polished.

The directions defined by the maxima of points of compression and tension thus may be constant throughout a varying but generally considerable volume of marble (so far as is known, as large as the volume of one quarry). In addition, it sometimes proves to be the case that these directions are independent in orientation of structures such as foliation, lineation and preferred orientation of [0001]-axes, features which are intimately related to a major penetrative deformation. The orientation of points of compression and tension can never be entirely independent of the orientation of [0001]-axes; for instance, if a compression is applied parallel to an [0001]-axis maximum, then no grains are in a position to twin an $\{01\bar{1}2\}$-plane. The position of a statistical maximum of points of compression or tension may thus be modified slightly by the preferred orientation of [0001]-axes, especially if it is strong. However, any departures in the constructed points of compression and tension from the actual points so caused will be present to a similar degree in all diagrams prepared from one homogeneous block. Another control of the orientation of the compression and tension points which should be appreciated is the purely geometrical one of a strong preferred orientation of [0001]-axes in a girdle, if the twinning is not produced by stress. The assumption that twin-

ning on $\{01\bar{1}2\}$ is induced by applied stress is made because of the statistical maxima which appear in diagrams constructed by measuring numerous grains in one thin section. However, suppose that the twinning is not mechanically induced and that the twinned lamallae are of random development. If a strong preferred orientation of [0001]-axes into a girdle with a pronounced maximum is present, then this will be accompanied in many instances (McIntyre and Turner, 1953, p. 233, fig. 4a and b) by a similar and coincident preferred orientation of the poles of $\{01\bar{1}2\}$-planes. This follows from the crystallography of calcite; but there appears in such cases to be an additional preferred orientation of $\{01\bar{1}2\}$-planes so that two out of the three in each grain lie with their poles in the plane of the [0001]-axis girdle. This orientation is demonstrated by the strong preferred orientation of the edges $[e_1{:}e_2]$ between strongly marked $\{01\bar{1}2\}$-lamellae (*e*-lamellae) in each grain into a single sharp maximum at *B* (McIntyre and Turner 1953, p. 235, fig. 5c and d). Thus, if there is fortuitous twinning of $\{01\bar{1}2\}$ planes at a late stage in the history of the marble, then the chances are two to one that the twin lamellae will lie with their poles in or near the plane of the [0001]-axis girdle. In addition, since there is a strong maximum of [0001]-axes in the girdle, and since the point of maximum tension (19° from [0001] by construction), [0001], the poles of $\{01\bar{1}2\}$, and the point of maximum compression (71° from [0001] by construction) lie in the same plane, the pattern of points of compression and tension, which must follow geometrically, is a maximum of points of tension coincident with but weaker than the [0001]-maximum, and a girdle of points of compression in the *ac*-plane with maximum concentrations 71° from the [0001]-maximum. This pattern could easily be misinterpreted as indicating a tension at the [0001]-axis maximum with a compression approximately 90° away in the *ac*-plane. Thus, patterns in which a maximum of points of tension coinciding exactly with the [0001]-maximum, and a maximum of points of compression in the *ac*-plane and approximately normal to the tension maximum, occur together should be doubted as a guide to the orientation of a possible system of stresses. Such patterns may be a faithful guide, but they may equally well be a geometrical consequence of preferred orientation of [0001]-axes. In a rock with a random orientation of grains, the constructed points of compression and tension would likewise be random if the $\{01\bar{1}2\}$ twin lamellae were not deformation structures.

It follows from the above considerations that strong maxima for points of compression and tension in grains of calcite with a weak preferred orientation must be significant. Even in marbles with a strong preferred orientation of [0001]-axes, if the constructed maximum for tension does not coincide with the [0001]-maximum, or if either or both the compression and tension maxima lie outside the *ac*-plane as defined by the [0001]-girdle, then the pattern of orientation of stresses so deduced must be significant. In most of the marbles from Greece analyzed below there is little doubt that the inferred axes of compression and tension are significant. In some specimens both maxima lie outside the [0001]-girdle; in others only one does so. Only

in specimens 1 and 6 do the tension maxima lie near the [0001]-maxima, and even so, the tension girdles spread not in the *ac*-plane but in a plane normal to the compression maxima.

The significance of the technique of plotting statistical applied stresses has been discussed in some detail because of the importance which will be attached to it in the following synthesis.

From the fabric of an equigranular marble with postkinematic crystallization we can expect to obtain two, three, or, very rarely, four directions, the mutual inclination and orientation of which will be constant for volumes of marble of limited size. These directions are defined by:

1. The maxima of [0001]-axes.
2. The axis of the girdle of [0001]-axes.
3. and 4. The maxima of points of compression and tension constructed from {0112} twin lamellae.

Only 2, 3 and 4 are likely to be an infallible guide to the orientation of a fragment, and even two of these may coincide. But in many marbles the three directions will be mutually inclined and will define a unique orientation of the fabric. When this state of affairs prevails, we can expect to be able to solve the first two and possibly, eventually, the third of the problems listed at the end of the first section.

ANALYSIS OF SEVEN SPECIMENS OF GREEK MARBLE

In order to decide how far the dominantly theoretical principles discussed in the last section apply to the more common Greek marbles, seven specimens collected from important quarries in Greece by N. Herz of the U. S. Geological Survey have been examined. The specimens are unfortunately unoriented, and no conclusions of regional importance can be drawn.

Table 1 records the data supplied by Herz concerning these specimens which now form part of the rock collection of the Department of Geological Sciences at the University of California at Berkeley. The numbering in the second column is based upon the British Military Mediterranean grid system: the first two numbers represent the east coordinate and the last two the north coordinate. The first two specimens are presumably the "Hymettian" marble and specimens three to six the "Pentelic" marble of the epigraphers. The seventh specimen is of Parian statuary marble from the island of Paros.

From each specimen two mutually perpendicular oriented thin sections were cut; ideally three should be cut, especially from a marble which is nearly isotropic. In each section 150 [0001]-axes were measured and points of compression and tension were plotted for between 20 and 25 grains markedly twinned on {0112} lamellae. Thus for each specimen three diagrams were obtained, one for [0001]-axes, one for points of compression, and one for points of tension in twinned grains. These diagrams are reproduced in figures 3 to 23. Table 2 summarizes the more obvious features of each specimen visible in hand specimen.

TABLE 1

	University of California Number	Herz Number	Coordinates on B.M.M.G.S.	Remarks by Herz
(1)	153-M-1	4241-1	42.5 x 41.2	From Mount Hymettus, just east of Athens, from an old Roman quarry apparently worked in modern times.
(2)	153-M-2	4241-Z	42.2 x 41.2	Same as (1)
(3)	153-M-3	5054-1c	50.7 x 54.3	From Mount Pentelicon, just north of Athens from the Spilia Daveli quarry. This was the largest of the ancient Greek quarries.
(4)	153-M-4	5054-2	—	Quarry just east of (3)
(5)	153-M-5	5056-2	50.85 x 56.5	From Dionysus quarries on north slope of Mount Pentelicon. Quarries date from last half of 19th century.
(6)	153-M-6	5153-1	51.25 x 53.4	From small ancient (?) quarries on southeast slope of Mount Pentelicon above Platanakia. These quarries are in narrow bands of marble dipping steeply in schist.
(7)	153-M-7	6238-1E	62.1 x 38.8	From ancient Lychnites marble mine, Aghias Minor, Paros. These mines produced the famous Parian statuary marbles.

TABLE 2

	Specimen	Color	Foliation, bedding or lineation
(1)	153-M-1	Faintly streaked with white and pale gray	The gray streaks in the rock are axial rather than planar. They constitute a faint lineation almost invisible upon any but a cut and polished surface.
(2)	153-M-2	Clean and white with very faint yellow streaks	No determinable structures can be seen in the rock except the faint yellow streaks which may define a crude foliation.
(3)	153-M-3	Clean white marble with some flakes of mica glistening on broken surfaces	A fairly pronounced linear structure is defined by the orientation of flakes of mica. No foliation is visible.
(4)	153-M-4	Red and green banded marble. Layers alternately rich in piedmontite and epidote form the colored bands.	The layers of piedmontite and epidote define a pronounced foliation which is folded (the fold axis is *B*).
(5)	153-M-5	Clean white marble	The rock is almost isotropic with no visible lineation or foliation.
(6)	153-M-6	Grayish white marble with very faint streaks	The streaks may define a crude banding but they are very weak and the pattern is uncertain.
(7)	153-M-7	Pure white marble	Appears to be completely isotropic with no foliation or lineation.

It can be seen from this table that the seven specimens include types which show no obvious macroscopic structures, others may show a weak foliation or lineation or both. All the marbles except 153-M-4 are very pure and the structures, especially foliation, are correspondingly ill defined. Their orientation would be determined in worked material, if at all, only with great difficulty. For this reason their orientation has not been shown upon the orientation diagrams.

From the data contained in figures 3 to 23 it is possible to construct "fabric pictures," one for each specimen, containing the salient features of the orientation diagrams. The data which can be recorded are as follows:

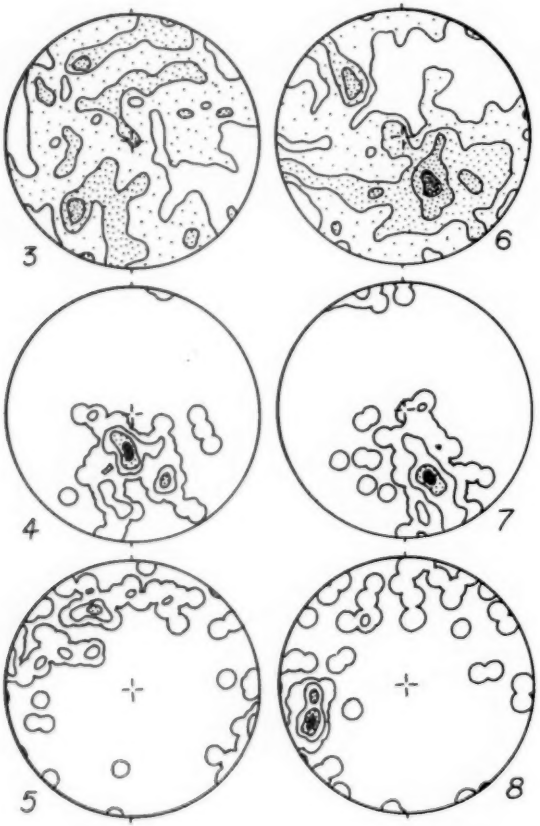

Fig. 3. 300 {0001}-axes in specimen 153-M-1. Contours: 1-2-3% per 1% area. Fig. 4. 50 axes of compression for twin lamellae in specimen 153-M-1. Contours: 2-6-10-14% per 1% area. Fig. 5. 50 axes of tension for twin lamellae in specimen 153-M-1. Contours: 2-6-10% per 1% area. Fig. 6. 300 {0001}-axes in specimen 153-M-2. Contours: 1-2-3-4% per 1% area. Fig. 7. 50 axes of compression for twin lamellae in specimen 153-M-2. Contours: 2-6-10-14% per 1% area. Fig. 8. 50 axes of tension for twin lamellae in specimen 153-M-2. Contours: 2-6-10-14% per 1% area.

1. The maximum M or maxima M_1, M_2, and so on, from the orientation diagrams for [0001]-axes. If one maximum is appreciably higher than all others, then only this should be recorded; if, however, there are several maxima of equal strength, then all should be recorded. Each maximum is recorded as the center of gravity of the area enclosed by the highest contour.

2. The great circle M_G defining the greatest spread of the [0001]-axes from the maximum M. If there are several maxima, then M_G should as nearly as possible pass through all of them. It is at best a compromise.

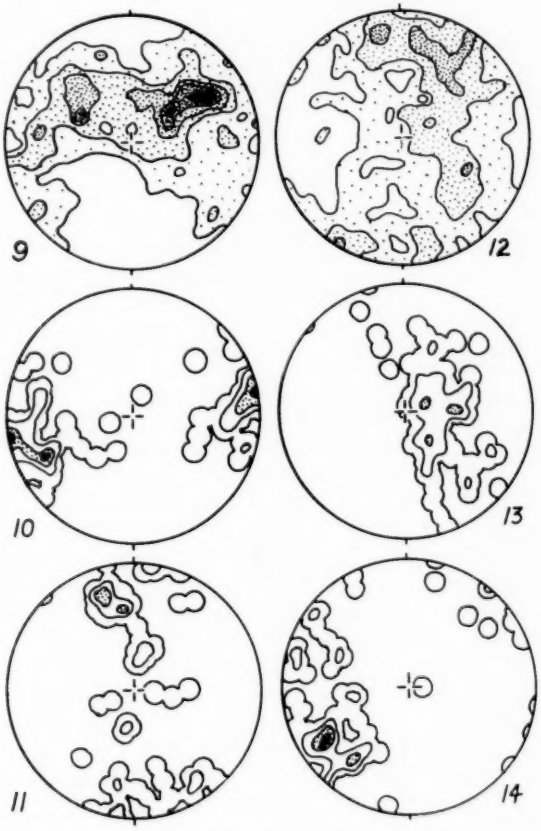

Fig. 9. [0001]-axes in specimen 153-M-3. Contours: 1-2-3-4-5% per 1% area. Fig. 10. 50 axes of compression for twin lamellae in specimen 153-M-3. Contours: 2-6-10-14% per 1% area. Fig. 11. 50 axes of tension for twin lamellae in specimen 153-M-3. Contours: 2-6-10% per 1% area. Fig. 12. 300 [0001]-axes in specimen 153-M-4. Contours: 1-2-3% per 1% area. Fig. 13. 50 axes of compression for twin lamellae in specimen 153-M-4. Contours: 2-6-10% per 1% area. Fig. 14. 50 axes of tension for twin lamellae in specimen 153-M-4. Contours: 2-6-10-14% per 1% area.

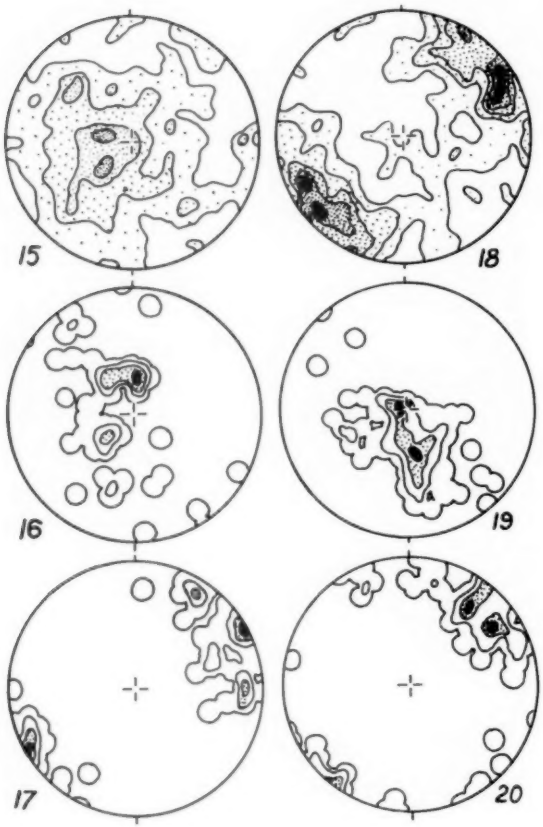

Fig. 15. 300 [0001]-axes in specimen 153-M-5. Contours: 1-2-3-4% per 1% area. Fig. 16. 40 axes of compression for twin lamellae in specimen 153-M-5. Contours: 3-6-9-12% per 1% area. Fig. 17. 40 axes of tension for twin lamellae in specimen 153-M-5. Contours: 3-6-9-12% per 1% area. Fig. 18. 300 [0001]-axes in specimen 153-M-6. Contours: 1-2-3-4-5% per 1% area. Fig. 19. 50 axes of compression for twin lamellae in specimen 153-M-6. Contours: 2-6-10-14% per 1% area. Fig. 20. 50 axes of tension for twin lamellae in specimen 153-M-6. Contours: 2-6-10-14% per 1% area.

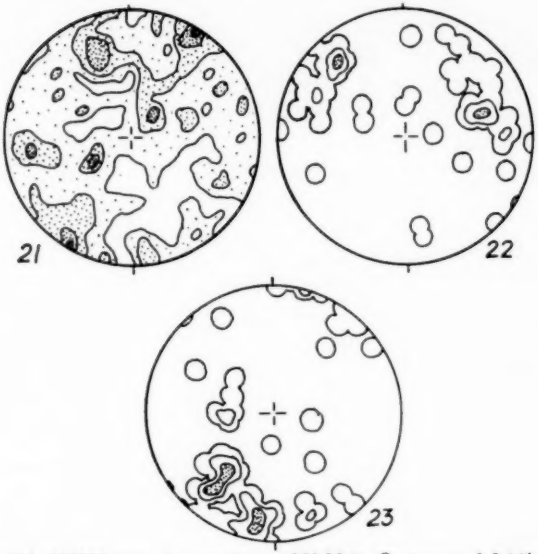

Fig. 21. 300 [0001]-axes in specimen 153-M-7. Contours: 1-2-3% per 1% area. Fig. 22. 40 axes of compression for twin lamellae in specimen 153-M-7. Contours: 3-6-9% per 1% area. Fig. 23. 40 axes of tension for twin lamellae in specimen 153-M-7. Contours: 3-6-9% per 1% area.

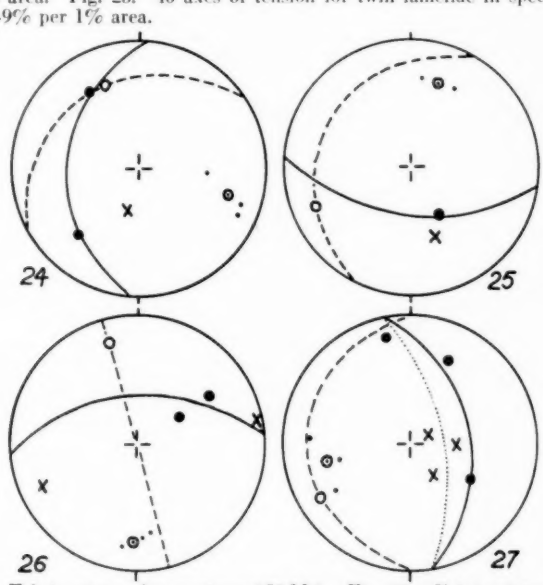

Fig. 24. Fabric picture for specimen 153-M-1. Fig. 25. Fabric picture for specimen 153-M-2. Fig. 26. Fabric picture for specimen 153-M-3. Fig. 27. Fabric picture for specimen 153-M-4. (In each diagram, small dots are A, L and pole of M_G; circle with dot is compromise B-axis; large dots are M, M_1, M_2; full line is trace of M_G; cross is C; dotted line is trace of C_G; open circle is T; broken line T_G.)

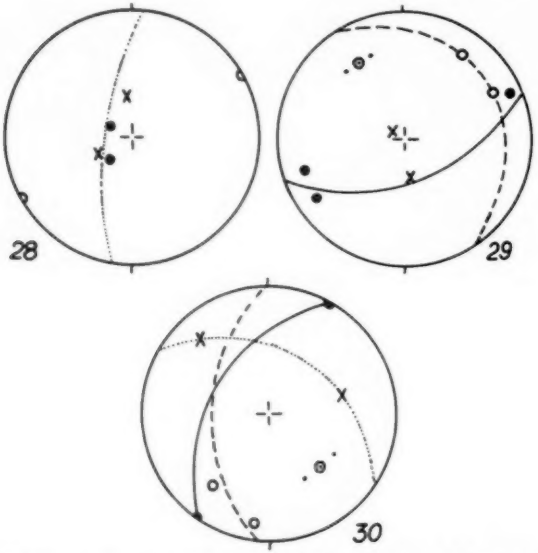

Fig. 28. Fabric picture for specimen 153-M-5. Fig. 29. Fabric picture for specimen 153-M-6. Fig. 30. Fabric picture for specimen 153-M-7. (In each diagram, small dots are A, L and pole of M_G; circle with dot is compromise B-axis; large dots are M, M_1, M_2; full line is trace of M_G; cross is C; dotted line is trace of C_G; open circle is T; broken line is trace of T_G.)

3. The center of gravity L of the largest area of zero concentration of [0001]-axes. For an orientation diagram showing a strong girdle concentration of [0001]-axes, L will be the pole of M_G; but where the girdle of [0001]-axes is wide and diffuse, L may diverge a greater or lesser degree from the pole of M_G. For a fabric which is weakly B-tectonitic the true B-axis (B) will be a compromise between L and the pole of M_G.

4. The maximum C or maxima C_1, C_2, and so on, for points of compression deduced from $\{01\bar{1}2\}$ twin lamellae. These also are plotted as centers of gravity.

5. In some instances the points of compression spread into a distinct girdle from C, C_1, and C_2. The trace of this girdle C_G should be recorded.

6. The maximum T or maxima T_1, T_2, and so on for points of tension, deduced from $\{01\bar{1}2\}$ twin lamellae.

7. The girdle T_G spreading from the maximum or maxima of points of tension.

8. The trace of a visible foliation or bedding plane S, where present, should be recorded; also any lineation or fold axis A which can be seen in the specimen. The center of the triangle of error L, A, pole of M_G should be taken as the B-axis in a marble which is a B-tectonite. Planar structures in the seven marbles are so weak that they have been omitted from the fabric pictures.

Most of the directions and planes defined above will help to fix the orientation of the specimen for which they are plotted. As has already been stated, not all of these data are reliable indices of orientation. The [0001]-maxima and the foliation and bedding planes can be used to determine the *B*-axis (the maxima lie on the *ac*-girdle and the foliation or bedding planes are tautozonal about *B*), after which they may be, for simplicity, removed from the fabric picture. The fabric pictures for the seven specimens are reproduced in figures 24 to 30. Each picture has the same orientation as the corresponding orientation diagrams in figures 3 to 23.

METHOD OF INTERPRETING FABRIC PICTURES AND ITS LIMITATIONS

General procedure.—The fabric pictures can be used in two ways to compare fragments of marble:

1. The salient features of the pictures should be directly compared. If they are similar in all of the important respects mentioned above, then it is likely that the fragments are part of one small body of marble. Obviously, unavoidable inaccuracies in the method of preparation of the orientation diagrams mean that the resemblance will be inexact; but complete dissimilarity of the fabric pictures will mean that the fragments from which they were prepared cannot have formed part of one small block.

2. Once it has been established that several fragments have similarity of fabric pictures strong enough to indicate a common origin, the triclinic symmetry which, in most examples, will be a feature of the fabric pictures, will define for the fragments a unique orientation. In order most easily to compare the pictures, those which show good axial control of fabric should be rotated until viewed along *B*. There are two senses to the direction *B*; but, if the pictures are plotted upon tracing paper, then they may be viewed also from back to front for purposes of comparing the opposite senses, provided that they are also rotated through 180° about *B* with relation to the specimen (fig. 31).

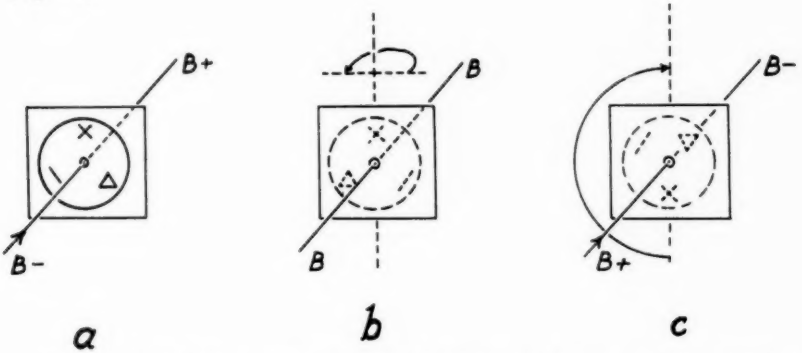

Fig. 31. Procedure in rotating tracing of orientation diagram in plane normal to *B* to view in opposite sense of *B*.

a. Orientation of tracing in relation to the two senses of *B*. Arrow shows the sense of viewing (*B*+).

b. First step; rotation of tracing around vertical axis.

c. Second step; rotation of tracing around *B*. The orientation diagram seen through the tracing paper is now viewed in the sense shown by the arrow (*B*−).

If the pictures show planar control of fabric, that is, [0001]-axis maxima without girdles, then they should be rotated until viewed along the direction defined either by the tension or the compression maxima (the more clearly defined direction is selected). There are two senses and the pictures can be viewed along either as shown in figure 31.

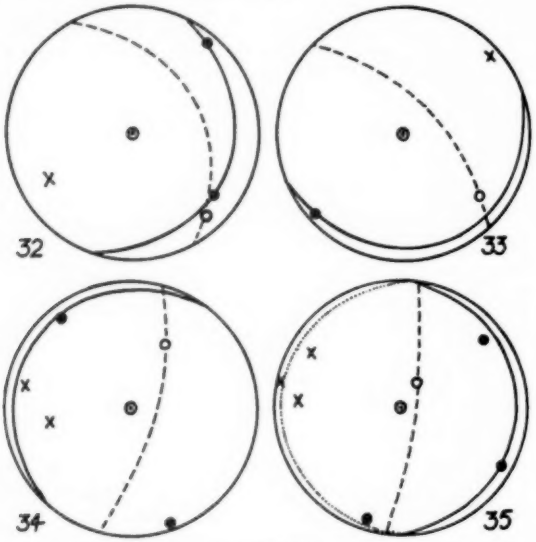

Fig. 32. Fabric picture for specimen 153-M-1 rotated until viewed along *B*. Fig. 33. Fabric picture for specimen 153-M-2 rotated until viewed along *B*. Fig. 34. Fabric picture for specimen 153-M-3 rotated until viewed along *B*. Fig. 35. Fabric picture for specimen 153-M-4 rotated until viewed along *B*.

The fabric pictures reproduced in figures 24 to 30 have been prepared from unoriented specimens. However, specimens 1 and 2 are from the same quarry on Mount Hymettus and the corresponding fabric pictures, when rotated until viewed down the compromise *B*-axis (figs. 32 and 33), show similarity. Unfortunately, this cannot be checked against a known orientation. Similarly, the fabric pictures for specimens 3 and 4, collected from adjacent quarries on Mount Pentelicon, have a mutual resemblance when rotated (figs. 34 and 35). Fabric pictures from the remaining specimens are reproduced in order to show that from a variety of Greek marbles distinct fabric pictures are obtained by analysis. The most weakly defined picture is that prepared from the Parian statuary marble (specimen 7); but even in this picture the maxima of compression and tension are distinct and the *B*-axis is defined by the preferred orientation of [0001]-axes (figs. 21 to 23 and fig. 30).

General procedure in examining a set of fragments believed to be part of one worked block should be as follows:

Procedure with fragments believed to be part of one stele.—This is the simplest case as the single inscribed surface presumably present upon each

fragment uniquely orients the fragments in relation to each other. Figure 36 shows a hypothetical restoration of a stele based upon the orientation defined by the inscribed surface. Certain fragments fit together along broken surfaces; for example, fragments 6, 8 and 9; 1 and 2; 3 and 4. This confirms immediately that each group formed part of a single block, but does not confirm that the three groups are similarly related. The circles inscribed upon the fragments contain hypothetical idealized fabric pictures prepared from the respective fragments. The similarity in the position of B, T and C in the pictures prepared from fragments 1, 2, 3, 4, 6, 8, and 9 confirm that they were part of the same stele. The homogeneity of the block also is established. The pictures for the remaining unattached fragments prove by their dissimilarity both from the other pictures and amongst themselves that they are not part of the main stele or even of one stele. The variation in position and size of M, M_1, M_2 shown in the pictures for the selected fragments in figure 36 is to show that such maxima can have considerable range in orientation in one block of marble. It is, however, important that the maxima should lie close to or on the great circle the pole of which is B.

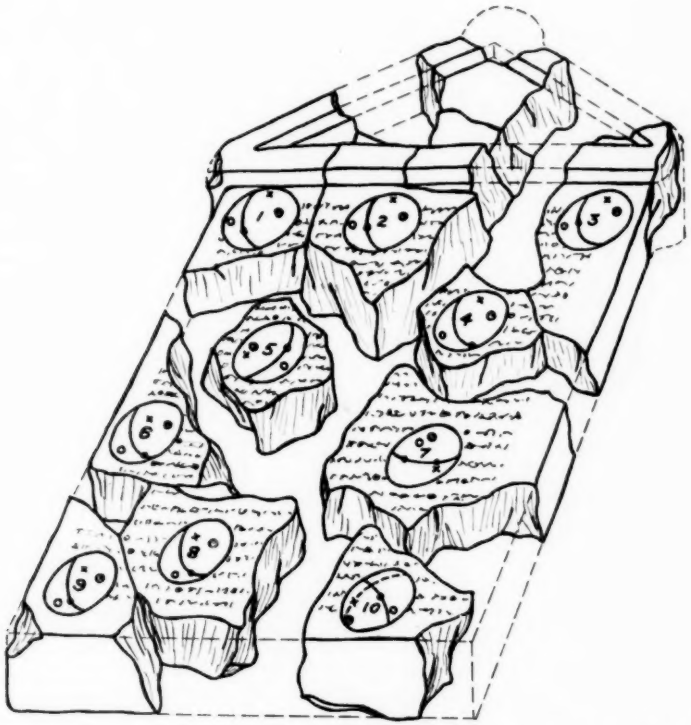

Fig. 36. Hypothetical restoration of a fragmental stele. Fragments 5, 7 and 10 are not part of the stele. (Full circle is trace of M_0: black dots are M, M_1, M_2: cross is C; broken line is C_0: open circle is T: circle with dot is B)

Procedure with fragments believed to be part of a work in marble other than a stele.—Treatment of such fragments presents much more difficulty and is open to more error than is the treatment of fragments of a stele. For some of the fragments there will be no morphological clue to relative orientation, although many fragments will have their orientations fixed to some extent: for instance, there is only a limited range of orientation of a foot or a head in relation to the trunk of a statue. The first stage in a work of restoration is to prepare fabric pictures from all large important fragments. If there is axial control of fabric the pictures should be rotated until viewed along *B*. The pictures then should be compared, and fragments with pictures which are obviously unlike the majority should be rejected at once. As in the last example, large fragments and groups of fitting fragments may be used to establish the degree of homogeneity of the fabric.

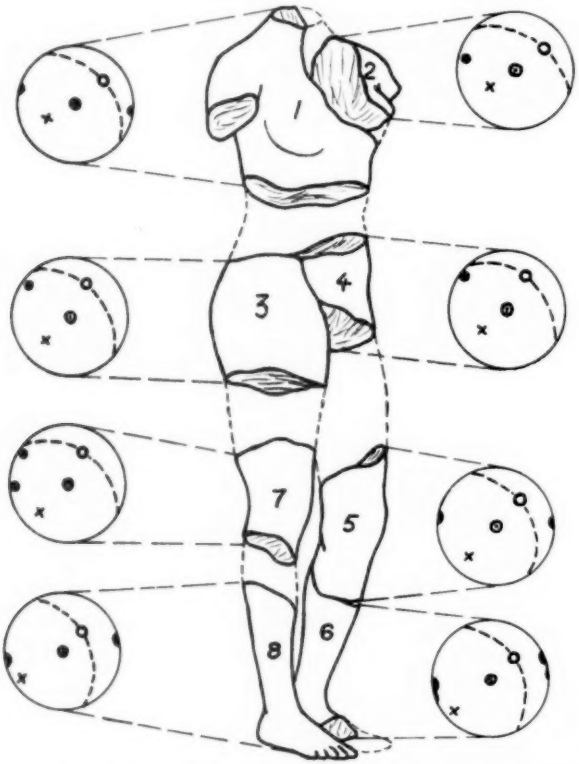

Fig. 37. Tracing of the Aphrodite of Cyrene showing mode of restoration if this statue had been found in fragmental and incomplete condition (only the head and arms are actually missing). The eight fabric pictures prepared from the eight fragments are rotated so that they are viewed along the same sense of the compromise *B*-axis. The relative orientation of the fragments so defined is thus fixed, and the only possible positioning of them is as shown.

It will generally be possible to establish homogeneity in a marble, and, once this has been done, the fragments selected for their mutual similarity of fabric pictures can be oriented with respect to each other. If, as will often be the case, the *B*-axis and the compression and tension maxima define a triclinic symmetry for the fabric picture, then the relative orientation can be

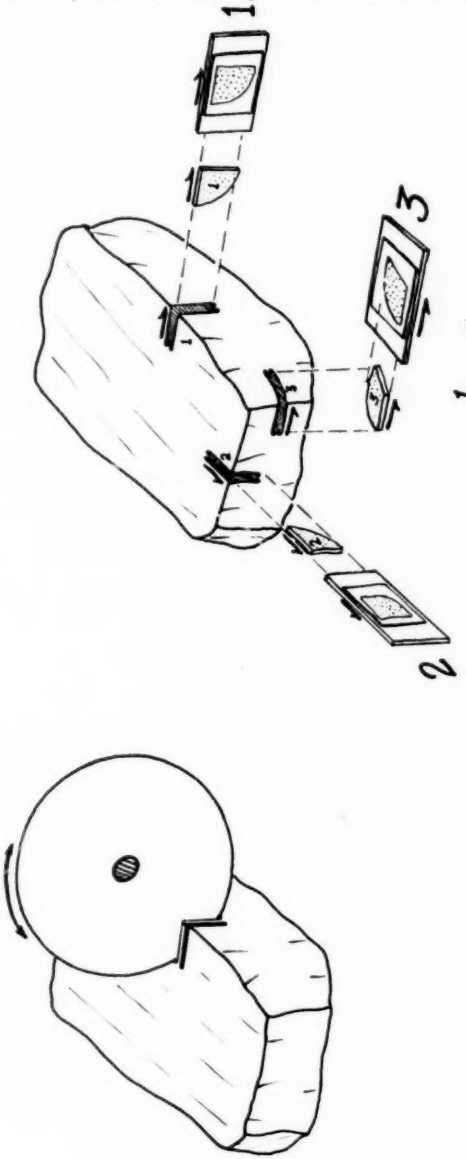

Fig. 38. Procedure in cutting and orienting thin sections.

a, Parallel saw cuts made with rotary saw.

b, Triangular leaves are snapped out and are made into three mutually perpendicular sections with known orientation.

determined with little difficulty. If, however, the symmetry of the picture is monoclinic (it is unlikely that it will be either orthorhombic or axial), then there will be two possible orientations for each fragment. Such ambiguities will in many instances be solved by considering the external form of the fragments. A hypothetical restoration of this type is shown in figure 37.

This technique of restoration is thus largely, as are so many structural techniques involving kinematic or dynamic interpretations, a matter of trial and error. No rule of thumb will ever be developed and each specific problem must be treated in a different manner. In many cases the technique should prove successful, in others it may fail; but in all it will require care, patience, and an ability to evaluate the significance of data such as could be possessed only by an experienced worker.

Procedure in cutting and orientation of thin sections.—Best results will be obtained by cutting *three* mutually perpendicular thin sections and measuring data from each. The resultant diagrams should be rotated into one plane and combined.

The actual cutting of thin sections from valuable fragments should be performed with great care by a skilled technician. Sections are best made from broken edges and surfaces of fragments as shown in figure 38-a. Two parallel saw cuts are made to a suitable depth as close together as the nature of the rock will allow, and a triangular leaf is snapped out, after marking its orientation with respect to the fragment. This leaf is carefully mounted and made into a thin section of which the actual orientation relative to the fragment is accurately known. Such sections are prepared from the three mutually perpendicular planes as shown in figure 38-b. As an additional check upon the orientation of the thin section the fragment, after cutting, should be drawn or photographed and the exact orientation of the finished sections shown. This whole operation should be conducted with utmost care and accuracy as upon it will depend the significance of the analysis.

After the sections have been cut, the narrow slots so left in the specimen are filled with plaster or another suitable filler, and the narrow band is colored most nearly to resemble the rock. If cutting is confined as far as possible to already broken surfaces, then the appearance of the fragment will not be harmed. Fragments with irregular or rounded surfaces may be dealt with in the same way.

Time involved in analysis.—The measurement of the data from the thin sections is a time-consuming procedure. In a medium-grained marble such as those described above, to measure 150 [0001]-axes and 25 twinned $\{01\bar{1}2\}$-lamellae in each of three sections and to rotate and contour the diagrams into one plane will take an experienced worker from 15 to 20 hours. In some marbles with fine grain the time required may be longer, whereas in other coarse-grained marbles, with plentiful and marked twinning, it may be shorter. To complete one restoration of, say, 10 fragments would take a minimum of 150 working hours. Most stelai should be dealt with in considerably less time than this, as the fragments will generally be much fewer in number.

SUMMARY OF CONCLUSIONS

The following conclusions are stated as simply as possible for use of geologist and archeologist alike:

1. Detailed fabric analysis of marble indicates that from any one specimen of marble a "fabric picture" may be prepared which in many instances will define a unique orientation in space for the specimen. The orientation is generally fixed by three directions:

(a) The compromise *B*-axis deduced from the [0001]-axis orientation of the grains of calcite and the megascopic lineation, where present.

(b) and (c) The statistical maxima of points of compression and tension deduced from twinning upon $\{01\bar{1}2\}$.

2. Previous work indicates that these three directions tend to have approximately constant orientation throughout bodies of marble of various size. It is likely that they will prove always to be constant in orientation throughout a block of a size suitable for inscription or sculpture.

3. Making use of the fabric pictures, it will be possible to restore a stele or other work in marble: firstly, by selecting those fragments which have sufficiently similar fabric pictures to be part of one block; and, secondly, by establishing the relative orientation of each fragment.

4. The seven specimens of Greek marble analyzed have all yielded strong and distinctive fabric pictures. This suggests that the principles outlined above will be applicable to many problems of ancient Greek art.

5. It is necessary to point out that this paper is a preliminary description of a technique which is at the moment still unapplied. It is difficult to find suitable problems outside Greece; and, before the work is carried too far in analyzing specific examples, it would be well to visit the more important quarries in Greece and establish the degree of homogeneity of the marble masses themselves. Incidental to this study, the orientation of large and small scale structures within the marble-bearing formations of Attica should be examined. The separate identity of the Hymettian and Pentelic marbles has been questioned by Kober (1929) and it is possible, as he suggests, that nappe structures exist in Attica. Mapping of axial structures in this region may well prove that much of the crystalline series of Attica is homoaxial, and it may be possible, by axial projection of a geologic map, to prepare a tectonic profile and establish a definite structural relation between the various bodies of marble. Also, axial control of fabric may be limited to certain well-defined bodies of marble, thus limiting marbles which are *B*-tectonites to certain places of origin.

Thus, application of the technique outlined above should be preceded, wherever possible, by a field investigation of the marble-bearing formations from which the worked fragments are thought to have been derived. Obviously, certain specific problems, such as the restoration of one fragmentary stele, could perhaps be solved with no knowledge of the field relations of the source marble; but systematic field investigation of the marbles in one general source area may eventually make possible not only the restoration of fragmentary works of marble but also the tracing of the quarry, or at least the general area from which the marble had been obtained. It should certainly

be possible to assign a marble to a country of origin; for instance, a Roman copy in Italian marble of a Grecian original should be distinguishable readily from a true Grecian work in marble from Greece.

It is possible that the field outlined in this paper can be enlarged considerably, perhaps, with increasing petrofabric knowledge, even to include the restoration of works in rocks other than marble; but much groundwork remains to be done before the techniques suggested can be established soundly and applied widely. There is no reason, however, why certain specific problems should not be tackled with the knowledge already to hand, as the writer intends to do in conjunction with Dr. W. Kendrick Pritchett of the University of California. There must be many archeological problems of the kind suggested which a small amount of work upon a small number of thin sections would solve simply and quickly.

ACKNOWLEDGMENTS

The writer wishes to record his thanks to Dr. F. J. Turner and Dr. W. K. Pritchett of the University of California who suggested the problem and gave guidance and advice. Thanks also are due to Dr. Norman Herz of the U. S. Geological Survey who provided the specimens of marble collected by him in Greece, and to Dr. D. B. McIntyre of the University of Edinburgh for reading the manuscript. The optical measurements were made with equipment purchased by the Moray Endowment.

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RELATIONS OF THE PROPERTIES OF WISCONSIN LOESS TO TOPOGRAPHY IN WESTERN IOWA*

ROBERT V. RUHE

ABSTRACT. Previous studies have shown that thickness, particle-size distribution, and other characteristics of the Wisconsin loess in western Iowa vary exponentially with distance from an assumed major source. The intensity of development of soils derived from Wisconsin loess has been related to the decreasing thickness of the loess that has been recognized as a function of increasing distance from the source. Detailed studies of the characteristics of Wisconsin loess show that previous concepts apply only to sample sites on the summits of primary and secondary divides. Characteristics of the loess show greatest values on the crests of divides and progressively decrease down the flanks of interfluves both toward and away from the assumed source of loess. Detailed studies of weathering profiles in Wisconsin loess show maximum intensity of development on the crests of divides but progressively decrease in intensity of development down the flanks of interfluves both toward and away from the assumed major source.

INTRODUCTION

Several investigations have shown the regional curvilinear relationships of certain characteristics of loess deposits. Krumbein (1937) demonstrated that the thickness of loess relative to its source could be expressed by exponential curves. In a study of loess-derived soils in Illinois, Smith (1942) showed that thickness, particle-size distribution, and carbonate content of the Peorian, as well as the Late Sangamon (now recognized as Farmdale), loess varied exponentially with distance from the assumed source. Properties of soils developed on the Peorian loess were shown to be related to the loess thickness.

Hutton (1947, 1951), following Smith's approach in a study of loess-derived soils in southwestern Iowa, demonstrated similar characteristics of loess relative to distance from an assumed source, the Missouri River Valley. Soils were noted to be related to the thickness of the loess along Hutton's traverses (fig. 1). In Holt County, Missouri, Shrader et al. (1953) followed a similar approach and arrived at similar conclusions.

In the previous studies few measurements and samples were taken along traverses of considerable distances. In Illinois, Smith's traverses of approximately 70 and 100 miles are represented by 10 to 15 measurements of thickness with correlative samples. In southwestern Iowa, Hutton's northern traverse of 167 miles had 11 measurement and sample sites, and the southern traverse of 87 miles consisted of 10 measurements and sample sites. Simonson and Hutton (1954) recently extended the southern traverse through 257 miles on the basis of a total of 11 measurements of loess thickness.

The recent relocation of the Chicago, Rock Island, and Pacific Railroad in southwestern Iowa between Atlantic and Bentley has offered an excellent opportunity to study Pleistocene deposits in the area (Ruhe, 1954). Fifty major cuts, some 60 to 70 feet deep and half to three-quarters of a mile long, transect the north-south ridges generally at right angles along the traverse of 34 miles (fig. 1 and fig. 2, A). Each cut exposes not only the complete sec-

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tion of Wisconsin loess surmounted by a level or slightly rounded summit but also the buried summits and flanks of the Sangamon surface on which the Wisconsin loess was deposited. Thus excellent sections are available for accurate measurement of thickness of the Wisconsin loess as well as a study of its other characteristics relative to the basal surface of deposition, the

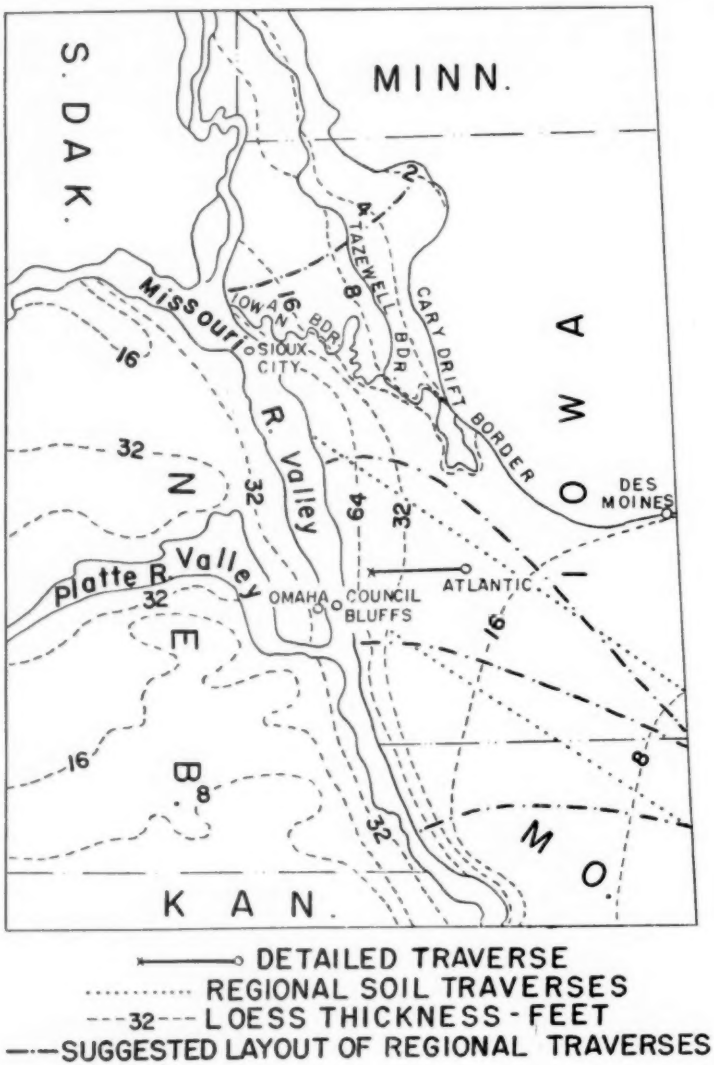

Fig. 1. Regional distribution of the thickness of Wisconsin loess and locations of traverses in western Iowa.

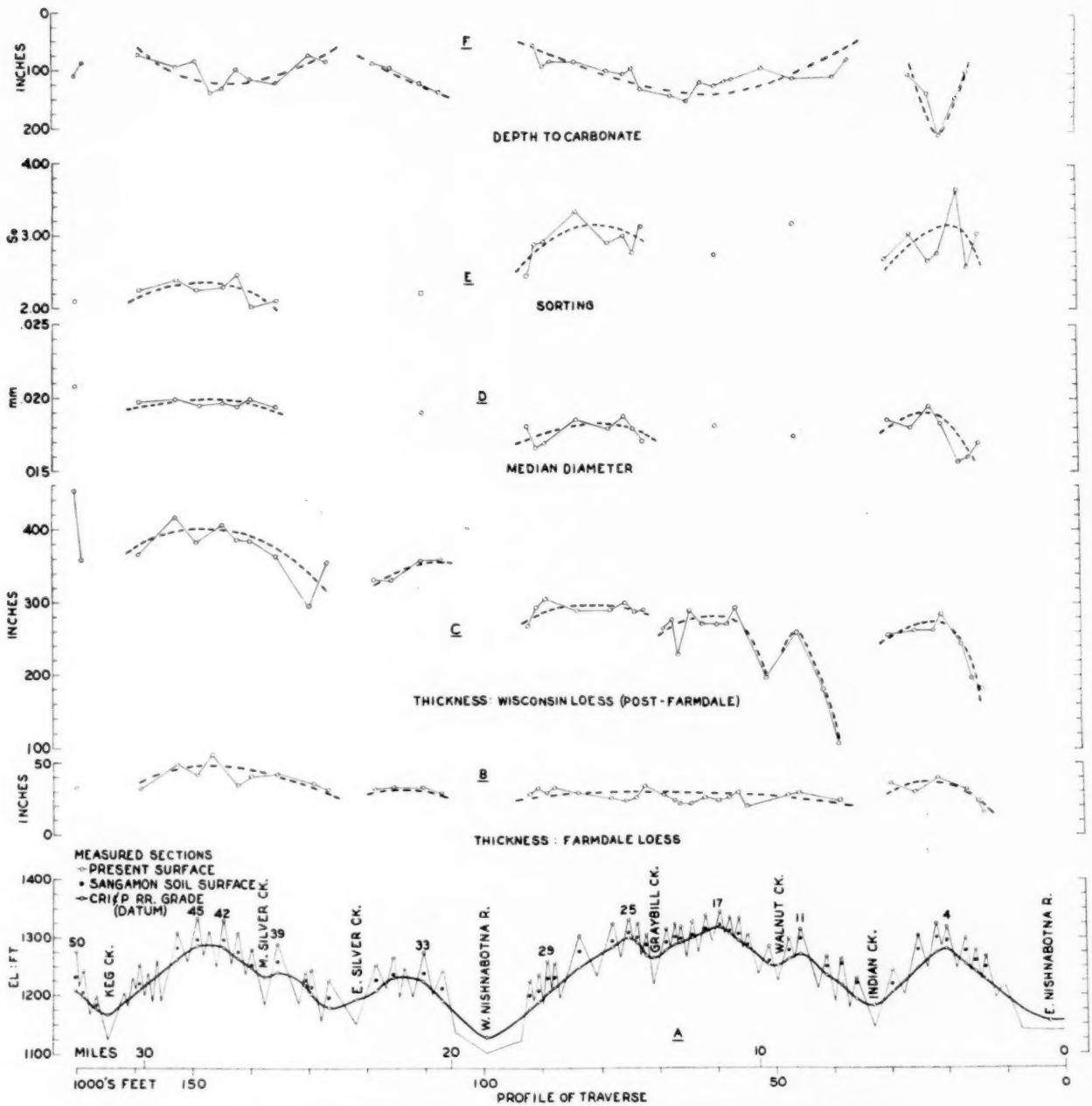

Fig. 2. Topographic profile and detailed curvilinear characteristics of Wisconsin loess along the Rock Island relocation in western Iowa. Note: topographic profile and curves of loess characteristics are lettered *A* to *F*; see text.

Sangamon surface. Selection of sites where post-loess erosion or other modification is at a minimum is facilitated by the cuts. The surveyed base grade of the Rock Island Railroad also serves as a controlled reference datum relative to distance and elevation. Thus, the exposure in the Rock Island cuts of 50 measurement and sample sites in a traverse of 34 miles affords an opportunity to compare the data of previous regional studies with the writer's detailed study.

REGIONAL CURVILINEAR RELATIONSHIPS

Figure 2, A shows that distribution of Wisconsin loess along the traverse is a curvilinear relationship of elevation to distance. The loess mantles the Sangamon landscape that stands highest at the primary divides. Primary divides are defined as the divides between the major drainages along the traverse. The major drainages are three: East Nishnabotna River, West Nishnabotna River, and Keg Creek, all tributary to the Missouri River. The primary divides are the heights of the Sangamon landscape at cut 17, and between cuts 42 and 45.

Secondary divides are those between main tributaries of the major drainages. Indian and Walnut Creek drain to the East Nishnabotna River. Cuts 4 and 11 are secondary divides within the East Nishnabotna system. Graybill, East Silver, and Middle Silver Creeks are affluent to the West Nishnabotna River. Cuts 25, 29, 33, and 39 are secondary divides within the West Nishnabotna system. Main tributaries to Keg Creek are not important within the reach of the stream transected by the loess traverse. All other divides are considered to be tertiary divides although some may be of a fourth or fifth order of magnitude. Because all drain to secondary drainages within short distances of the traverse, they are categorized in the same order of divide-magnitude.

The Sangamon surface slopes from the primary and secondary divides to the present primary and secondary drainages. A parallelism exists between the buried Sangamon surface and the modern surface (post-Wisconsin loess). The basic control of the expression of the modern loessial landscape is the buried Sangamon surface. Thus an analysis of the development of the modern landscape, that is essentially one of loess deposition but modified somewhat by post-loess erosion on slopes, should analyze also the surface on which the Wisconsin loess was deposited, the Sangamon surface.

Previous investigators have utilized the modern surface as the basis of their landscape analyses. Smith (1942, p. 149), Hutton, (1947, p. 424), Simonson and Hutton (1954, p. 102) selected modern level to slightly rounded divides as sites for measurement of loess thickness and sampling. They assumed that any possibility of significant changes in thickness of loess through erosion or deposition of wash from adjacent higher land was precluded at these topographic positions.

Application of the regional research approach has been made by the present writer to the cuts along the Rock Island relocation. Sample sites were selected at the positions of primary and secondary divides, namely cuts 50, 45, 42, 39, 33, 29, 25, 17, 11, and 4 (fig. 2, A). The data are presented in figure 3.

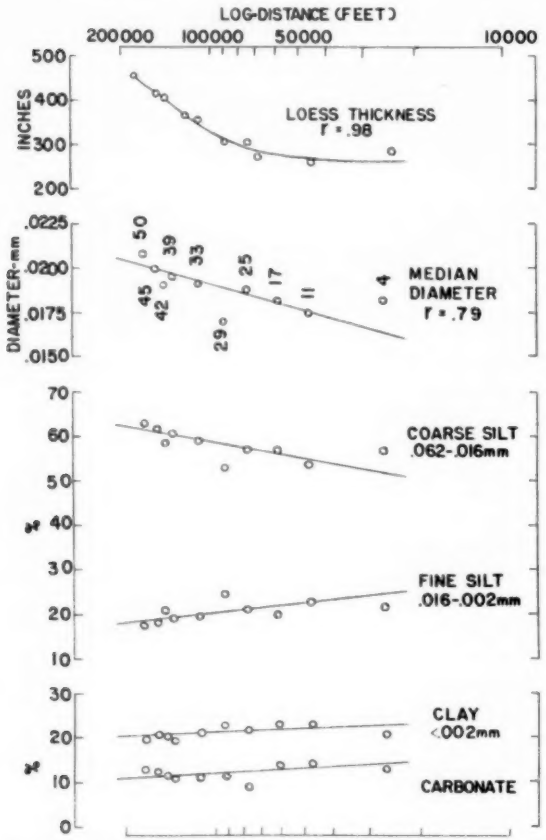

Fig. 3. Regional curvilinear characteristics of the Wisconsin loess along the Rock Island relocation in western Iowa.

The thickness of the loess systematically decreases with distance from an assumed source, the Missouri River Valley, from 453 inches at cut 50 to 285 inches at cut 4. This west-to-east traverse transects the regional loess-thickness lines at approximately a right angle in the west half of the traverse, but deviates from a normal to the loess thickness lines in the east half of the traverse (fig. 1). The latter deviation precludes an ideal traverse layout, but the deviation was unavoidable in order to take advantage of the railroad cuts. However, the traverse crosses all divides at approximately a right angle. The thickness data when tested statistically show a correlation coefficient of $r = 0.98$, indicating that the expected relationship, decrease of loess thickness with distance from the assumed source, is present.

Median diameters of oxidized and unleached, i.e., the least-weathered, loess from divide locations also systematically decrease from west to east along the traverse. The median-diameter data when tested statistically show

a correlation coefficient of $r = 0.79$, also indicating that the expected relationship, decrease of median-particle diameter with distance from source, is present.

Other texture data are in accord with these relationships. The coarser silt fraction (.062-.016 mm) systematically decreases, and the finer silt fraction (.016-.002 mm) as well as the clay fraction (< .002 mm) increase with distance along the traverse.

The carbonate content was found to increase with distance from the assumed source. In Illinois Smith (1942, p. 164-172) found that carbonate content systematically decreases with distance. Along the Rock Island traverse in Iowa, the increase is apparently the effect of secondary concentration of fine carbonate in the oxidized and unleached loess due to weathering processes. Carbonate determinations of particle-size fractions showed:

Cut	*Total*	*Coarser silt fraction*	*Finer silt fraction*	*Clay fraction*
50	12.6%	60.8%	42.2%	15.0%
33	11.2	60.5	22.3	17.2
11	14.0	42.8	29.8	27.4

The above data conform with and substantiate the regional studies of previous workers. Although Simonson and Hutton (1954, p. 100-101) suggest that traverses in western Iowa should be laid out in a southeasterly linear direction from the Missouri River Valley, consideration should be given to laying out loess traverses in regional studies in a curvilinear pattern so that the regional loess-thickness lines are crossed at right angles (fig. 1). Exponential equations of thinning of loess (Hutton, 1947) should vary considerably if linear and curvilinear traverses are compared. Secondly, if soils along loess traverses are to be compared, linear traverses may give a false association. Segments of different linear traverses may fall along one curvilinear traverse (fig. 1).

In northwestern Iowa, the loess thins in a curvilinear manner toward the northeast in contrast to the southeasterly curvilinear pattern in southwestern Iowa. The geographic distribution pattern could be accounted for by generally westerly winds removing sediment from a major source, the east-west trending Missouri River Valley between South Dakota and Nebraska, and distributing the sediment in a broad fan-shaped pattern to the east. Complexities in sedimentation are to be expected along the western margin of Iowa because of the near source of sediment in the south-trending Missouri River Valley. Complexities in sedimentation are to be expected also in northwestern Iowa because of loessial sedimentation contemporaneous with the recessions of the Iowan and Tazewell glaciers to the northeast.

LOCAL CURVILINEAR RELATIONSHIPS

Compilation of the data of the Wisconsin loess of each cut along the Rock Island relocation presents a picture of loess characteristics entirely different from that shown by only the regional samples of primary and secondary divides. Measurements and samples were taken at every cut, primary, secondary, and tertiary divides, where the loess is surmounted by a level or slightly rounded summit. Thus, the requirement is fulfilled of sample sites

where significant post-loess erosion or post-loess deposition by wash essentially is precluded. Of 50 cuts, 8 were discarded as measurement sites because the cuts occur on north or south slopes along the trends of the ridges. Each sample site is similar, in a local sense, to all others, but they differ in that the secondary divide sites are located on the flanks of primary divides. The tertiary divide sites, in turn, are located on the flanks of secondary and primary divides (fig. 2, A). For example, 7 sample sites are located across the secondary divide between the East Nishnabotna River and Indian Creek. Each ridge, cuts 1 through 7, at the sample site is a level to slightly rounded summit. Cuts 5, 6, and 7 occur progressively lower on the west flank of the secondary divide surmounted by cut 4. Cuts 3, 2, and 1 occur progressively lower on the secondary divide. Similar divide units are located along the traverse:

Cuts	*Divide*	*Part of traverse*
8-12	Secondary	Indian Creek-Walnut Creek
13-22	Primary	Walnut Creek-Graybill Creek
23-31	Secondary	Graybill Creek-West Nishnabotna River
32-35	Secondary	W. Nishnabotna River-E. Silver Creek
36-46	Primary	East Silver Creek-Keg Creek

Occurring in each cut in the basal part of the Wisconsin loess and above the Sangamon soil is a thin leached zone characterized by a weakly developed buried soil (generally an A-C profile). This basal loess, incorporated entirely within the buried soil, is correlated by the writer with the Farmdale of Illinois (Leighton and Willman, 1950, p. 602-603). Above the Farmdale and progressively upward are weathering zones in the Wisconsin loess designated as deoxidized and leached zone, oxidized and unleached zone, deoxidized and unleached zone, and oxidized and leached zone (Ruhe, 1954, p. 640). In the upper part of the oxidized and leached zone, a soil classified as the Monona silt loam occurs generally west of cut 33, and to the east the soil is generally the Marshall silt loam.

Inspection of the data, thickness of Farmdale loess relative to distance along the traverse, shows that a mean curve of the values parallels the general topographic positions of the Farmdale sites upon the Sangamon surface (fig. 2, B). For example, across the primary divide between Keg and East Silver Creeks, the maximum thickness of Farmdale loess occurs at the crest of the divide. The Farmdale loess thins progressively down the flanks of the divide both to the west, *toward* the loess source, and to the east, *away* from the loess source. Similar relationships exist across the other divide units along the traverse.

The following discussion pertains to the Wisconsin loess that is post-Farmdale in age, and the term Wisconsin loess, for the sake of brevity, will be restricted to the post-Farmdale increments. Inspection of the data (fig. 2, C), thickness of Wisconsin loess relative to distance along the traverse, shows more distinctly the correlation of thickness of Wisconsin loess to topographic position on the Sangamon surface. Any modification by the thin Farmdale increment is slight. The relationships, thickness of loess to distance along the traverse, are:

Divide unit	*Part of traverse*	*Characteristics*
Primary	Keg Creek-E. Silver Creek	Maximum thickness at crest of divide: progressive thinning on divide flanks to west and east.
Secondary	East Silver Creek-West Nisnabotna River	Maximum thickness at crest of divide: progressive thinning on divide flanks to west and east.
Secondary	West Nishnabotna River-Graybill Creek	Maximum thickness at crest of divide: progressive thinning on divide flanks to west and east.
Primary	Graybill Creek-Walnut Creek	Maximum thickness at crest of divide: progressive thinning on divide flanks to west and east.
Secondary	Walnut Creek-Indian Creek	Maximum thickness at crest of divide: progressive thinning on divide flanks to west and east.
Secondary	Indian Creek to East Nishnabotna River	Maximum thickness at crest of divide: progressive thinning on divide flanks to west and east.

The relationship, maximum thickness of loess at crests of divides with progressive thinning on divide flanks both in a westerly direction, *toward* the loess source, and an easterly direction, *away* from the loess source, differs radically from the generally accepted concept developed in regional studies that loess thickness decreases exponentially with distance from the source.

It seems apparent that another factor other than a simple distance relationship may control the thickness distribution of loess. The general parallelism of the thickness curves to the topographic curves (fig. 2, A, C) suggests that configuration of the surface upon which the loess was deposited may influence the thickness distribution of the loess. The surface of deposition is the Sangamon surface, and in a macrosense is a rough surface. The thickness of loess relative to a rough surface of deposition may be evaluated by comparing the thickness of the loess at any point on that surface with the elevation of the surface of deposition at that point (fig. 4). The data may be tested statistically. Correlation coefficients determined for divide units are r values of 0.68, 0.77, 0.77, 0.86, 0.87, indicating that the thickness of loess deposited upon a surface is influenced by the elevation of the surface at the point of deposition. This cause and effect is restricted to individual units of the rough surface, i.e., individual divide units along the traverse. The correlation does not hold across several adjacent divide units. For example, the correlation coefficient of data across the multiple divide unit, West Nishnabotna River to Indian Creek is $r = 0.42$.

Thinning of loess on the flanks of divides is generally uniform both west and east. There is not a greater accumulation on one side of the divide than on the other, but the mantle is generally symmetrical to axes of the crests of the Sangamon surface. Individual cuts in general show the same symmetry of Wisconsin loess mantle on the Sangamon surface. Greatest accumulations of loess occur above the crests of the buried Sangamon surface. General statements in the literature report that in western Iowa greater thicknesses of loess occur on the east sides of hills or ridges (Kay and Graham, 1943,

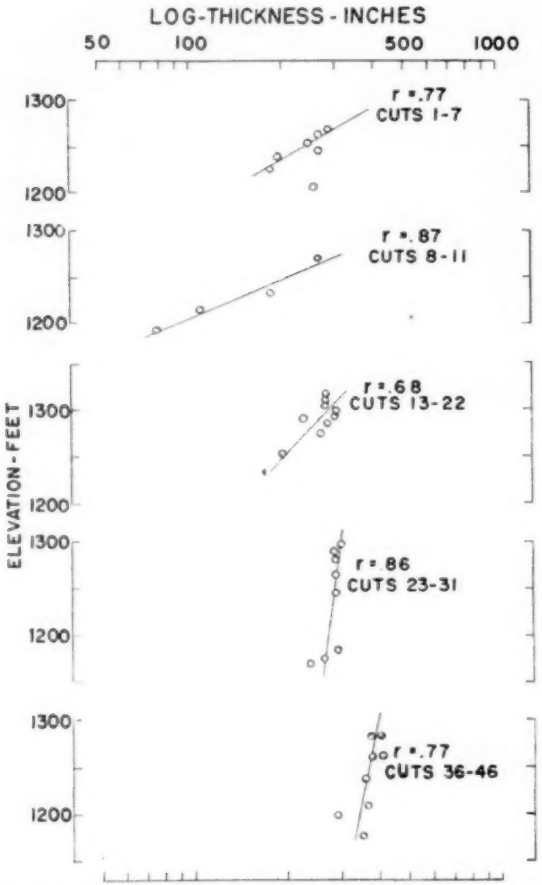

Fig. 4. Correlation of the thickness of Wisconsin loess and the elevation of points on the Sangamon surface at which loess was deposited.

p. 161) or the southeast sides of ridges (Simonson and Hutton, 1954, p. 100). Such asymmetrical loess accumulations have been used as evidence of lee-slope deposition to support interpretations of prevailing winds during loess deposition. The following data are presented as a contradiction to the assumed asymmetry of hills:

Number of cuts	*Wisconsin loess-mantle configuration on Sangamon surface*
45	Symmetrical
4	Asymmetrical (to east)
1	Asymmetrical (to west)
50	

Scale drawings of all cuts have been constructed. Earthmoving operations in cut construction completely penetrated the Wisconsin loess and went deeply

into pre-Wisconsin hill and ridge cores. In the writer's experience asymmetry of loess mantle is restricted to the narrow belt of bluff hills immediately east of the Missouri River Valley.

Inspection of the data presented in median diameter and sorting curves (fig. 2, D, E) shows a correlation with each other and the thickness distribution across the divide units. Median diameters are greater at the crests of divides and progressively decrease on divide flanks in both a westerly and easterly direction, i.e., both *toward* and *away* from the loess source. Previous regional concepts held that mean particle-size decreases with distance from the source. The sorting curves indicate that poorer sorting (greater *So* values) occurs at the crests of the divides. Sorting becomes progressively better (lesser *So* values) down the flanks of divides both west and east, i.e., both toward and away from the assumed source of loess.

These data, thickness distribution and variability in texture and sorting across local divides, when evaluated in regard to regional curvilinear relationships, show that loess sedimentation is complex and not just a simple function of distance from source.

LOCAL CURVILINEAR RELATIONSHIPS AND WEATHERING

Considerable work has been done on the physical and chemical properties of loess-derived soils relative to thickness of parent material along regional traverses. Bray (1934, 1937) and Smith (1942) pioneered this type of study in Illinois. Following the work of Hutton (1947, 1951) in western Iowa, other investigators (Ulrich, 1950, 1951; Godfrey and Riecken, 1954) have shown the progressive increase in the intensity of weathering of the sola. These changes in physical and chemical characteristics have been correlated with decreasing thickness of the loess as a function of distance from the assumed major source, the Missouri River Valley. No previous detailed studies have been made of local variability of soils across primary and secondary divides.

The data presented in figure 2, F indicate that such a detailed soil study may be desirable. The weathering profiles (Scholtes et al., 1951, p. 296-297) were examined and measured at each cut along the Rock Island traverse. Each measurement site was selected so that a level or slightly rounded summit surmounted the section. The mean curves representing depths to carbonates across the interfluves show an inverse relationship to the loess thickness, median diameter, and sorting curves. Greatest depths of leaching occur on the crests of divide units. Progressively lesser depths of leaching occur down both the west and east flanks of interfluves, i.e., both toward and away from the assumed source of loess.

Because a regional correlation exists between the physical and chemical properties of soils derived from Wisconsin loess relative to loess thickness, particle-size distribution, and degree of sorting, the question may be raised whether the local inverse relationship across interfluves of weathering to loess thickness, particle-size distribution, and degree of sorting may not be reflected in different properties of soils on the flanks of divides relative to crests.

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PROBABLE OCCURRENCE OF OLIGOCENE ON SAIPAN*

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ABSTRACT. An assemblage of mainly planktonic Foraminifera from southern Saipan, Mariana Islands, contains seven species in common with the *Globigerinatella insueta* zone of the Caribbean Tertiary. This zone, in the Caribbean, falls in the lower part of an interval which micropaleontologists working in that area call upper Oligocene, but which others consider to include both high Oligocene and low Miocene. The most distinctive and significant of the species common to both areas, all planktonic forms, are *G. insueta* itself and two new species, which are described in an appendix to this note. The finding of these fossils on Saipan offers hope for a solution to the vexing problem of the whereabouts of the Oligocene in the open Pacific and re-emphasizes the potential significance of planktonic and pelagic fossils for long-range correlation.

The occurrence cited is in marine tuffs that are interbedded with andesitic lava flows and overlain with abrupt angular and erosional unconformity by lower Miocene (Tertiary *e*) limestone. Underlying beds were not observed in the same succession, but different assemblages of smaller Foraminifera were obtained from lithically similar beds of latest Eocene age elsewhere on Saipan.

The likelihood of late Oligocene volcanism on Saipan combines with indications of Miocene volcanism on Yap and Guam, with widespread primary volcanic rocks of Eocene age, and with the active and Pleistocene volcanoes of the northern Marianas to imply that volcanic activity along the outer arcs of the Philippine Sea was recurrent through Cenozoic time. The idea of essential restriction of volcanic activity in the eastern Philippine Sea to the Eocene and Quarternary thus apparently no longer holds, though volcanism may have been accentuated at these times.

INTRODUCTION AND SUMMARY OF EVIDENCE

This note announces the finding on Saipan, in the Mariana Islands, of an assemblage of smaller Foraminifera that contains distinctive planktonic species in common with the *Globigerinatella insueta* zone of the Caribbean Tertiary. That zone marks the *lower* part of an interval which is called upper Oligocene by micropaleontologists currently working with it, but which is considered by others to include both high Oligocene and low Miocene. The *G. insueta* zone itself, therefore, presumably consists wholly or mainly of beds generally accepted as late Oligocene. If the occurrence of free-floating Caribbean key species on Saipan is taken to denote approximate stratigraphic equivalence, the implications of that occurrence for Tertiary correlation as well as for the geologic history of the western Pacific are so significant that it seems desirable to make the essential facts and provisional conclusions promptly available to other workers. It is intended later to provide a detailed description of these fossils and the formation in which they occur in a comprehensive report on the geology of Saipan.

Rocks regarded as both Oligocene and pre-Aquitanian have not to our knowledge previously been reported from the region south of Japan, north of New Guinea, east of the Philippines, and west of California. The previously reported "Oligocene" of the Mariana, Bonin, Ryukyu, and Daito Islands, where not Eocene, seems to be equivalent to Tertiary *e* of the Indonesian sequence (e.g., Tayama, 1939). Tertiary *e*, in turn, is a faunal zone that is most commonly referred to the Aquitanian stage of the standard European section. The Aquitanian, in its turn, is considered by some (Weaver, *et al.*, 1944; authorities cited in Glaessner, 1953, p. 651) to be Oligocene, whereas

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others (Cooke, *et al.*, 1943; authorities cited in Glaessner, 1953, p. 651; present authors) prefer to regard it as basal Miocene. Cloud and Cole (1953), following the latter practice, stated that no Oligocene had yet been recognized in the Mariana Islands. In the meantime, however, comparative studies of smaller Foraminifera from Saipan have revealed the supposedly upper Oligocene assemblage herein described in andesitic tuffs previously classed as upper Eocene on lithic and structural grounds.

Foraminiferal evidence.—1. The assemblage of smaller Foraminifera here recorded is intermediate in its overall composition between the early Miocene and late Eocene associations found on Saipan.

2. Of the six planktonic species that comprise most of the specimens so far obtained from this new stratigraphic unit, three appear to be specifically identical with species that are distinctive of the reputedly upper Oligocene *Globigerinatella insueta* zone of Trinidad in the British West Indies and of Venezuela. These three are: *Globigerinatella insueta* Cushman and Stainforth, *Globigerinoides subquadrata* Bronnimann, n. sp.[1], and *Globigerinoides bispherica* Todd, n. sp.[1] The ranges of these and other species, as currently understood, are shown in figure 1.

3. The planktonic species *Orbulina universa* d'Orbigny and *Globorotalia menardii* (d'Orbigny), generally regarded as Miocene species, have not been found in the beds that contain *Globigerinatella insueta* on Trinidad and Saipan. They occur abundantly at higher stratigraphic levels in both regions, however.

4. Of the species that occur rarely in the new unit, one of the planktonic and three of the benthonic species are believed to be specifically identical with species found in but not restricted to the partly or mainly Oligocene Cipero formation of Trinidad. These are *Orbulina suturalis* Bronnimann, *Karreriella chilostoma* (Reuss), *Siphogenerina seriata* (Cushman and Jarvis), and *Trifarina bradyi* Cushman. In addition to these four, several others are closely related to forms present in the Cipero formation.

As summarized in figure 1, the general balance of species present and missing thus suggests approximate equivalence with the *Globigerinatella insueta* zone and the lower part of the *Globorotalia fohsi* zone, of probable late Oligocene age on Trinidad. The monospecific genus *Globigerinatella* in fact is said to occur throughout this interval and to be restricted to it.

Local stratigraphic succession.—The beds containing the fauna under discussion are a part of an incomplete succession of interbedded andesitic flows and marine tuffs that dip 3° to 10° eastward beneath subhorizontal limestones (fig. 2) that contain larger Foraminifera considered to be of Tertiary *e* (early Miocene) age.[2] The fossils suggest deposition in relatively deep water (perhaps as much as 400-500 meters) for the tuffs, and water of

[1] See appendix of present report for descriptions of new species. These species are in current use by economic paleontologists as key species to the upper Oligocene of the Caribbean region.

[2] Including species identified by W. Storrs Cole (letter of March 3, 1954, to Cloud) as *Cycloclypeus* (*Cycloclypeus*) *eidae* Tan, *Eorupertia semiornata* (Howchin), *Lepidocyclina* (*Nephrolepidina*) *sumatrensis* (Brady), *L.* (*N.*) *verbeeki* Newton and Holland, and *Miogypsina* (*Miogypsina*) *thecideaeformis* (Rutten) (field localities C-82, C-87, and C-88). Field localities are shown on figure 2.

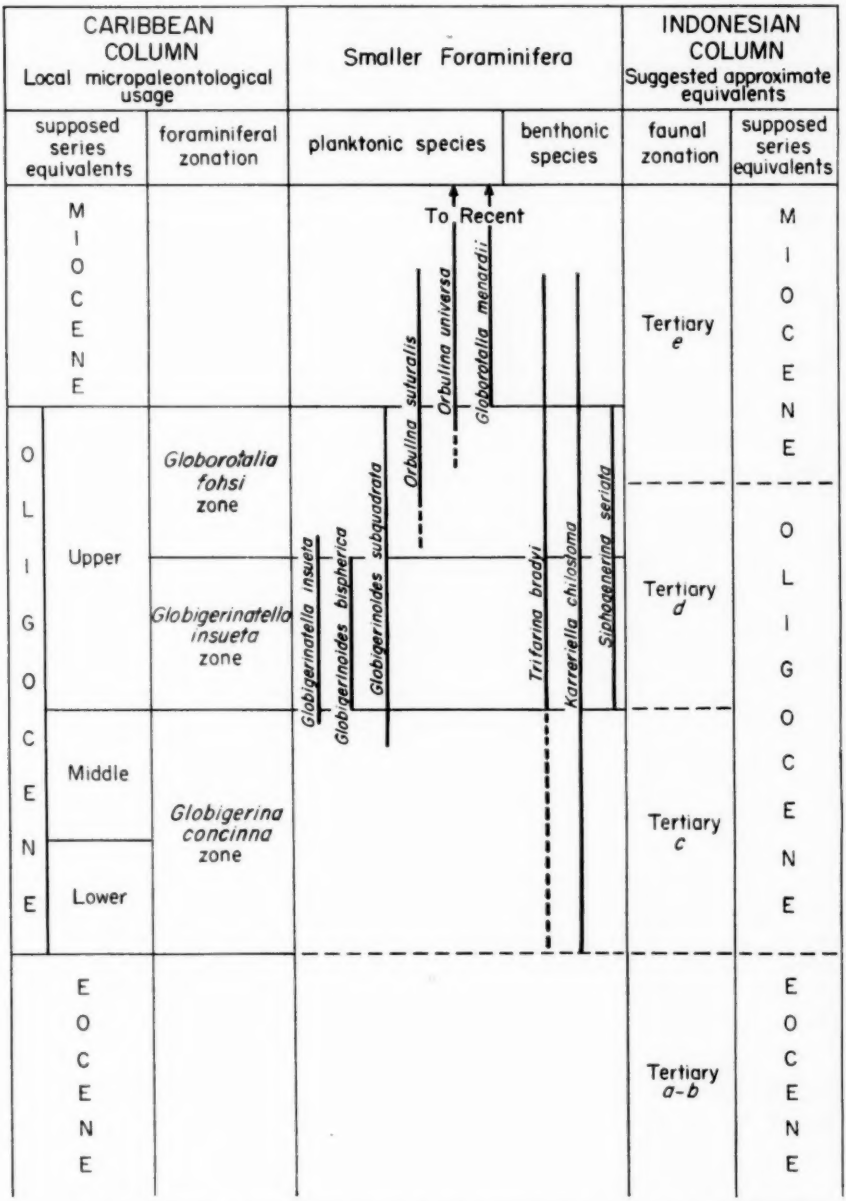


Fig. 1. Currently understood ranges in the Tertiary of Trinidad of species common to Trinidad and Saipan (data from Stainforth, 1948b, and from previously unpublished information provided by Bronnimann and Stainforth).

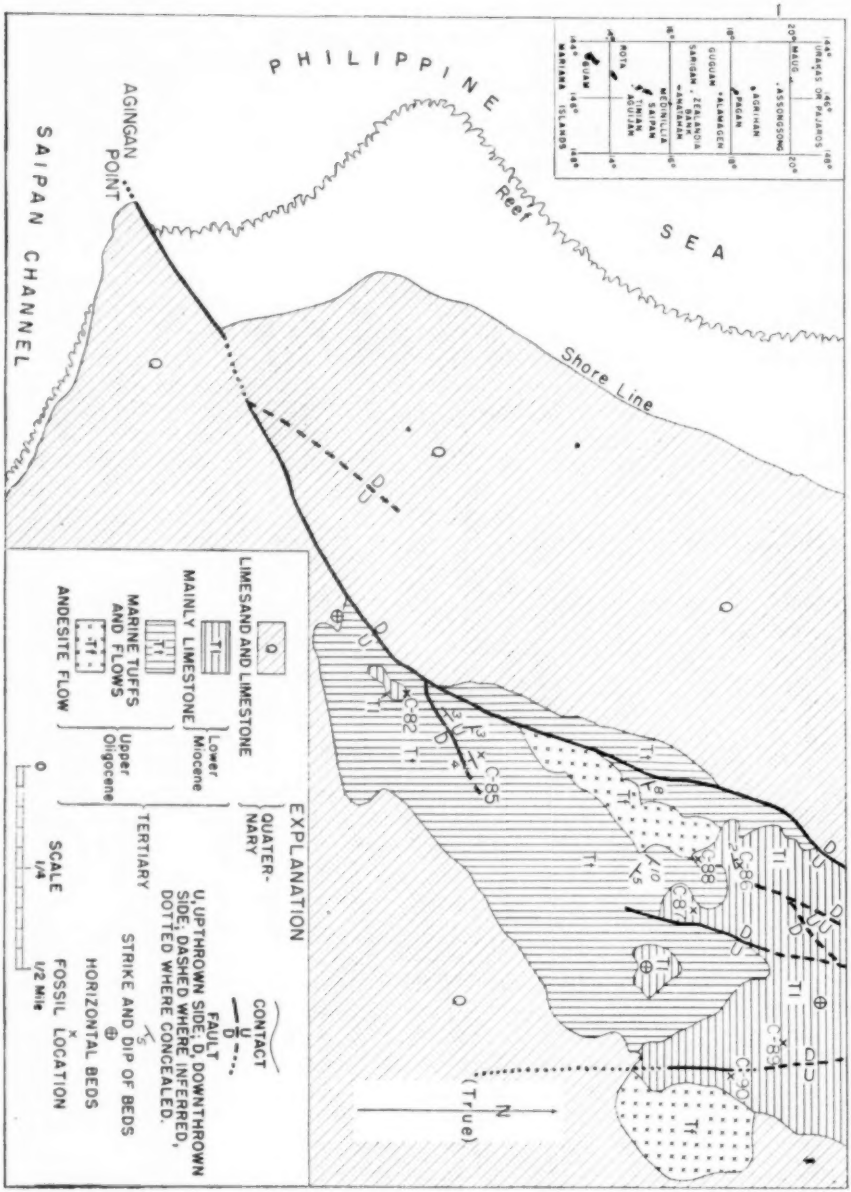


Fig. 2. Geologic map of the southwest corner of Saipan (geology by P. E. Cloud, Jr., 1948-1949).

moderate depth (roughly 100 meters) for the overlying limestones. The lower Miocene limestone overlaps approximately 400 feet of the supposedly Oligocene tuff-flow sequence to the faulted base of the exposed section. Because of this faulting, the immediately underlying beds are unknown. The early Miocene fossils in the capping beds, however, indicate an earliest Miocene or pre-Miocene age for the tuffs and flows beneath them, and the fossils so far found in the tuff-flow sequence do not support an Eocene age assignment. An earliest Miocene or Oligocene position is thus implied, and the markedly unconformable relationship with overlying known early Miocene lends weight to available fossil evidence in favor of an Oligocene age.

FURTHER CONSIDERATION OF FAUNAL EVIDENCE

The supposedly Oligocene smaller Foraminifera have been found at two localities but are abundant at only one of these (C-85, 1.6 miles northeast of the seaward tip of the southwest point of Saipan, fig. 2). This assemblage of smaller Foraminifera is ecologically similar to but faunally intermediate between that found in tuffaceous sandstones of Miocene age and that of the Eocene marine volcanic deposits of Saipan. The ecologic resemblance between the three units of presumably different age is in the great abundance of planktonic species, the occasional presence of benthonic species belonging to living genera of known moderately deep-water habitats, and the absence of known shallow-water forms. On the other hand, 44 of a total of 62 species appear to be restricted to the intermediate foraminiferal assemblage and have not been found in beds of Tertiary *e* (early Miocene) or Tertiary *b* (late Eocene) age on Saipan. Thus, about 70 percent of this assemblage is unique to it on Saipan, about 10 percent of its species have Eocene affinities, and about 20 percent are conspecific with forms known from the Miocene of Saipan.

In further contrast to both the Eocene and the Miocene foraminiferal assemblages, the one under discussion includes a greater predominance of planktonic over benthonic specimens. About 25 percent of its species and 95 percent or more of its specimens are planktonic, as compared with about 25 percent of the species and 75 percent of the specimens in the Miocene of similar facies and 5 percent of the species and 60 percent of the specimens in the Eocene. Of its 15 planktonic species, 6 are abundant. In order of decreasing abundance these are: *Globigerinoides bispherica* Todd, n. sp.* (pl. 1, fig. 1), *G. subquadraia* Bronnimann, n. sp.* (pl. 1, fig. 8), *G. triloba* (Reuss), *Globigerina?* sp., *Globigerinoides* sp., and *Globigerinatella insueta* Cushman and Stainforth* (pl. 1, fig. 2). The starred species are those shared with the upper Oligocene of the Caribbean region. Other planktonic species that are rare or infrequent in beds here referred to the Oligocene on Saipan include *Globigerina bulloides* d'Orbigny, *Orbulina suturalis* Bronnimann* (pl. 1, fig. 6), *Globoquadrina altispira* (Cushman and Jarvis),* *G. dehiscens* (Chapman, Parr, and Collins), and *Sphaeroidina hauerі* (Czjzek).

In addition to the 15 planktonic species, about 47 benthonic species are present, all rare or extremely rare, belonging mostly to the families Lagenidae, Heterohelicidae, Buliminidae, Ellipsoidinidae, Rotaliidae, Cassidulinidae, Chilostomellidae, and Anomalinidae.

In the category of negative evidence, the fauna here considered lacks the following distinctive planktonic species, which occur abundantly in the Miocene (Tertiary *e*) of Saipan: *Globigerinoides conglobata* (Brady), *G. rubra* (d'Orbigny), *G. sacculifera* (Brady), *Orbulina universa* d'Orbigny, *Pulleniatina obliquiloculata* (Parker and Jones), *Sphaeroidinella dehiscens* (Parker and Jones), *S. kochi* (Caudri), *S. seminulina* (Schwager), *Globorotalia menardii* (d'Orbigny), and *G. tumida* (Brady). In Trinidad also *G. menardii* makes its first known appearance in the early Miocene (cf. Aquitanian), in clays above the Cipero formation and well above the highest occurrences of *Globigerinatella insueta* and *Globigerinoides bispherica* (Bronnimann, letter of Oct. 2, 1953, to Todd). *Orbulina universa* d'Orbigny, whose first appearance may be of wide stratigraphic significance (Finlay, 1947, p. 337-340; LeRoy, 1948), comes into the section only a little below *G. menardii* in Trinidad.

Globigerinoides index Finlay, *Globorotalia centralis* Cushman and Bermudez, and *Hantkenina*,[3] all distinctive of the upper Eocene on Saipan, also are missing from the supposedly Oligocene strata there.

So far as we know, the most nearly comparable record of smaller Foraminifera from the Pacific region yet published is the assemblage listed by Finlay (1946) from the Oxford chalk of New Zealand and assigned to the "Whaingaroan stage." The Whaingaroan is currently referred to the lower Oligocene by New Zealand geologists. From Finlay's check list alone (no illustrations were given) the Foraminifera of the Oxford chalk would appear to represent a relatively deep-water facies; but the assemblage is much richer in species, and the planktonic species are fewer than in the possibly Oligocene fauna from Saipan. Of the 124 species listed from the Oxford chalk, only two (*Trifarina bradyi* Cushman and *Karreriella chilostoma* (Reuss)) can be definitely recognized in the Saipan material, and these, as already noted, have long stratigraphic ranges.

CORRELATION

The affinities of the new foraminiferal fauna from Saipan appear to be with the planktonic and relatively deep-water, presumably upper Oligocene *Globigerinatella insueta* assemblage of the Caribbean region (Cushman and Stainforth, 1945; Stainforth, 1948a, 1948b). Both R. M. Stainforth and Paul Bronnimann have examined samples of the material from Saipan and recognize strong similarity between it and the foraminiferal assemblages from the *G. insueta* zone in eastern Venezuela and the middle Cipero formation of Trinidad (letters of May 19, May 23, and June 1, 1953, to Todd). Moreover, as the Atlantic and Pacific oceans connected across Central America through the greater part of Tertiary time (Simpson, 1950, p. 363, 379-381), there is little likelihood of serious lag in distribution of tropical planktonic elements from the Atlantic to the Pacific realm, or the reverse.

[3] To be sure, *Hantkenina* apparently ranges into the Oligocene in America (Howe, 1928) and perhaps in Indonesia according to W. Mohler (van Bemmelen, 1949, p. 90, text fig. 26). However, Thalmann (1942, p. 817-818) questions Oligocene records of the genus, and on Saipan *Hantkenina* has been found only in association with rocks dated as late Eocene on the basis of nummulitid and discocyclinid Foraminifera.

The strata that contain *Globigerinatella* in Trinidad are underlain by beds that contain middle or late Oligocene (supposedly Rupelian or Chattian) megafossils (Stainforth, 1948b, p. 1310). In their upper part (basal *Globorotalia fohsi* zone) they are interbedded with or overlain by beds that contain mollusks believed by Rutsch to be late Oligocene and approximately Chattian (Stainforth, 1948b, p. 1311). If, therefore, *Globigerinatella* and its associates mark an approximate time horizon, their occurrence on Saipan would appear to be late Oligocene—perhaps approximately Chattian of the standard section.

On the other hand, the evidence for correlation with European faunal stages is not conclusive, the lineages of the species held in common between Saipan and Trinidad have not been worked out, and comparable assemblages from intervening regions are unknown. Pending the accrual of needed evidence on lineages and distribution, therefore, an unqualified age assignment for the Saipan occurrence is postponed. In the meanwhile, however, we believe that the available evidence, as here set forth, is suggestive enough of a late Oligocene age to warrant such a provisional correlation. To delay this announcement, pending discovery of areally intermediate occurrences, seems inadvisable because of the large element of chance involved in finding beds of the right sedimentary facies in the right part of the stratigraphic column between Saipan and Trinidad.

SIGNIFICANCE

Should this provisional correlation be correct, the occurrence of late Oligocene volcanism on Saipan would combine with evidence of Miocene volcanism on Yap (Tayama, 1939; confirmed by larger Foraminifera collected by Charles Johnson and studied by Cole and Cloud) and Guam (J. I. Tracey, Jr., oral communication to Cloud), with widespread primary volcanic rocks of Eocene age along the eastern Philippine Sea margin, and with the active and Pleistocene volcanoes of the northern Marianas to indicate that volcanic activity along the outer arcs of the Philippine Sea was recurrent through Cenozoic time. Although volcanism does appear to have been more markedly widespread and prolonged in Eocene than in later Tertiary time, and Quaternary volcanism is conspicuous in the northern Marianas and near Japan, this information also appears to negate the suggestion of Cloud (Cloud and Cole, 1953, p. 324) that volcanism in the southern Marianas was essentially an Eocene event. The correlation suggested in addition opposes the sometimes expressed or implied (but apparently not specifically published) view that the western and central Pacific may have been widely emergent during Oligocene time.

Finally, the foraminiferal assemblage here noted, together with large assemblages now being described from the upper Eocene (Tertiary *b*) and lower Miocene (Tertiary *c*) of Saipan, will contribute to closing the gaps in presently known distribution of smaller Foraminifera from the Tertiary of the Indo-Pacific. The planktonic Foraminifera and other planktonic and pelagic organisms even offer hope of eventually establishing an acceptable correlation with the standard European stage succession and between widely separated insular areas.

APPENDIX[4]

DESCRIPTIONS OF NEW SPECIES

(by Paul Bronnimann and Ruth Todd)

Globigerinoides subquadrata Bronnimann, n. sp.

Plate 1, figures 5, 8

The general outline of the test is subquadrate. The major portion of the test is represented by the three-chambered final volution. The early portion of the test is distinctly trochoid. It is only slightly smaller than the antipenultimate chamber. The subglobular and appressed chambers of the final volution increase rapidly in size, and the end chamber is equal to or only slightly smaller than the preceding part of the test. The ultimate and penultimate chambers are added perpendicularly to the preceding oral face. The initial spiral is indistinct and the spiral side is much like the umbilical side. The umbilicus is very shallow. The arcuate main aperture is situated at the intersection of the umbilical sutures; the smaller, also arcuate, accessory aperture is opposite the main aperture on the spiral side. Additional accessory apertures of the early spiral are visible only in large and well-preserved speci-

[4] We are indebted to Paul Bronnimann for permitting his description of *Globigerinoides subquadrata* n. sp., a species he had previously recognized in Trinidad, to be published here in order that reference might be made to it in the preceding discussion.

PLATE 1

Four species of upper Oligocene planktonic Foraminifera in common between Saipan and Trinidad*

Explanation of Plate 1

(All figures approx. X 84)

Figures 1, 4. *Globigerinoides bispherica* Todd, n. sp.

1. Saipan, loc. C-85. Holotype, a dextrally coiled specimen. U.S.N.M. no. 548876.
4. Trinidad, Ste. Croix beds, *s.s.*, Ste. Croix (Lothians) Quarry, S. of Princes Town, Naparima region. Ventral view of a dextrally coiled specimen for comparison with ventral view of holotype directly above. Cushman Coll. no. 54689a.**

Figures 2, 3. *Globigerinatella insueta* Cushman and Stainforth.

2. Saipan, loc. C-85. U.S.N.M. no. 548884.
3. Trinidad, Cipero formation, Zone H, sample no. Rz. 108. Paratype. Cushman Coll. no. 44042a.**

Figures 5, 8. *Globigerinoides subquadrata* Bronnimann, n. sp.

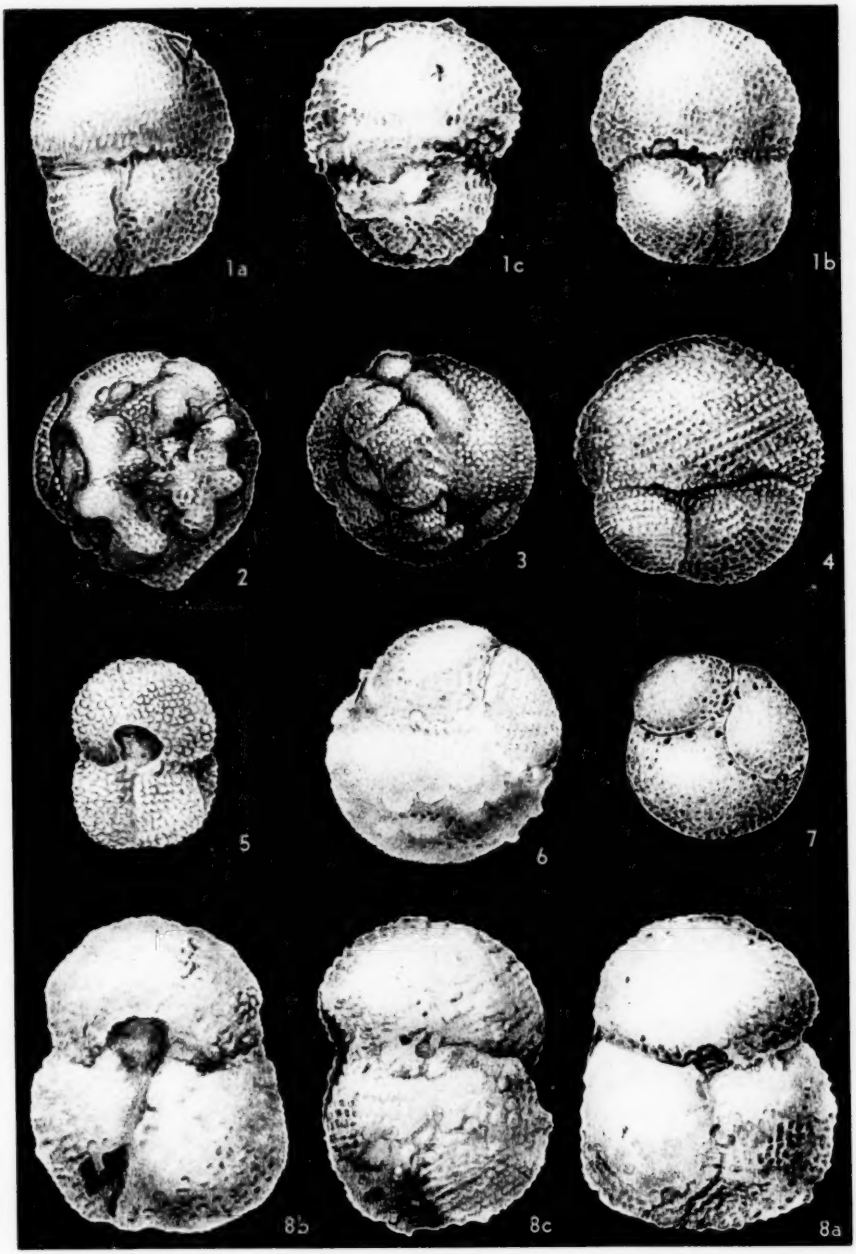
5. Trinidad, Cipero formation. Ventral view of a small, excellently preserved, sinistrally coiled specimen for comparison with ventral view of holotype directly beneath. U.S.N.M. no. 548882.
8. Saipan, loc. C-85. Holotype, a large but less well preserved sinistrally coiled specimen. U.S.N.M. no. 548881.

Figures 6, 7. *Orbulina suturalis* Bronnimann.

6. Saipan, loc. C-85. U.S.N.M. no. 548885.
7. Trinidad, Naparima area. Redrawn after Bronnimann (1951, p. 132, text fig. H, fig. 4). Diagrammatic drawing shows position of irregular sutural openings which are not ordinarily visible and are not visible in figure 6.

* Figures 1 and 8 each represent a single specimen, with orientation and arrangement of views indicated by the letter symbolism conventionally used for the smaller Foraminifera. Suffix *a* indicates a dorsal view, *b*, a ventral (or apertural or umbilical) view, and *c*, a peripheral view. Illustrations are arranged so that the peripheral view is invariably central, while rotation 90° to the right or left of the peripheral plane is indicated by a corresponding location to the right or left of the peripheral view. A dextral specimen thus has the ventral view at the right side (1*b*) and a sinistral specimen has its ventral view at the left (8*b*).

** The Cushman Collection is now a part of the United States National Museum collections of Foraminifera in Washington, D. C.


1a
1c
1b
2
3
4
5
6
7
8b
8c
8a

mens. The main aperture is bordered by large pustules. The well-defined sutures of the end stage are straight. Those of the initial stage are slightly curved. The walls are finely perforate and the surface is covered with strong and rather uniform pustules. The species coils to the right and to the left. The length of the test ranges from 0.35 mm to 0.6 mm.

Dimensions of the holotype: length, 0.58 mm; diameter of end chamber, 0.4 mm; diameter of the two preceding chambers, 0.47 mm; diameter of main aperture, ±0.11 mm; diameter of accessory aperture of end chamber, ±0.07 mm.

Holotype (U.S.N.M. no. 548881) from the upper Oligocene, 1.6 miles northeast of the seaward tip of the southwest point of Saipan (loc. C-85, fig. 2).

The species is distinguished by its symmetrical, subquadrate test and indistinct initial spiral, and by the main aperture being situated directly opposite the suture line.

This species occurs very abundantly in the upper Oligocene of Saipan. The same form is known as an undescribed index fossil for the Oligocene of Trinidad and eastern Venezuela. A specimen, showing better preservation of the wall surface than the Saipan specimens, is illustrated from the Cipero formation of Trinidad (pl. 1, fig. 5).

Globigerinoides bispherica Todd, n. sp.

Plate 1, figures 1, 4

Globigerinoides conglobata Cushman and Stainforth (not Brady), 1945, Cushman Lab. Foram. Research Special Pub. 14, p. 68, pl. 13, fig. 6.

Globigerinoides cf. *conglobata* Cushman and Renz (in part) (not Brady), 1947, *idem*, Special Pub. 22, p. 41.

Globigerinoides conglobata Stainforth (not Brady), 1948, Jour. Paleontology, vol. 22, p. 121, pl. 26, fig. 4.

Test consists of two spheres of equal or nearly equal size, confluent in greater or less degree, one sphere consisting of the last-formed chamber, the other sphere consisting of the penultimate chamber strongly embracing all the previous ones, coiling dextral and sinistral. Sutures distinct and incised in individuals where the chambers are less embracing, indistinct in individuals where the chambers are more embracing. Wall calcareous, perforate, ornamented by a dense pattern of small, delicate, round cancellations. Apertures two or more: in the case of individuals where the chambers are more embracing the apertures are irregular, narrow fissures appearing to result from the breaking apart of the test wall at the suture lines or suture junctions and usually bordered with irregular knobs of clear shell material; in the case of individuals where the chambers are less embracing the apertures are more distinct, low-arched openings into the final chamber, overhung by the rough, knobby edge of the chamber. Length 0.55-0.65 mm, greater diameter 0.45-0.50 mm.

Holotype (U.S.N.M. no. 548876) from the upper Oligocene, 1.6 miles northeast of the seaward tip of the southwest point of Saipan (loc. C-85, fig. 2).

This is the most abundant species in the upper Oligocene of Saipan. As described, it includes a rather wide range of shapes but is characterized by its bispherical form. Further studies of early Tertiary globigerinids are needed to determine the evolutionary relatives of this species.

The species has also been recorded under other names (see synonymy above) from the upper Oligocene of Trinidad and Ecuador. It is reported (R. M. Stainforth, letter of July 30, 1953, to Todd) to have had its acme during the short life-range of *Globigerinatella insueta* and to serve as a useful substitute marker for *G. insueta* in Venezuela where the latter is much less common than in Trinidad.

This species differs from *Globigerinoides subquadrata* Bronnimann, with which it occurs, in its circular, not compressed test, its less widely open apertures, and its finely cancellated wall. The individuals with strongly embracing chambers when poorly preserved may be confused with *Orbulina suturalis* Bronnimann and with *Globigerinatella insueta* Cushman and Stainforth but are distinguished by the faint trace of an equatorial suture line.

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STRATIGRAPHIC CORRELATION BY MICRO-FACIES

RHODES W. FAIRBRIDGE

ABSTRACT. Study of random thin sections of sedimentary samples (by micro-facies and depositional petrofabrics) has become standard practice among many oil companies, some even adopting mass production methods. This procedure does not involve a new technique for the evaluation of sediments, but over the last few decades it has become adopted more and more as a basis for improving stratigraphic correlation. Thin sections are used as a means of lithologic comparison from known sequences, the micro-facies often displaying individual characteristics that may be traced over thousands of miles.

Ecologic interpretation of the sedimentary petrofabrics is still in its infancy, but even the primary value of the fabric for general stratigraphic correlation still awaits widespread recognition and application. Attention is drawn to Cuvillier's volume of photomicrographs of the French Aquitaine sequence and to a proposal that a series of such publications might help with a revised standard for worldwide stratigraphic correlation.

INTRODUCTION

Intensive stratigraphic investigation by oil companies during the last decade or so has demonstrated that in favorable environments reliable long-range stratigraphic correlation can be carried out by a relatively simple technique. This, in general, requires less skill and basic training than the time-honored methods of macro- and micropaleontology, and can be extended over wide regions, well beyond the local petrographic provinces that normally limit correlation by electric well-logging or the usual techniques of sedimentary petrology. The method involves the cutting of large numbers of thin sections, from which may be observed characteristic and distinctive fabrics that are representative of both micro-biofacies and micro-lithofacies and may prove to have far-reaching equivalents.

An incidental but important sidelight on the value of the thin-section method of stratigraphic analyses is the astonishing reduction in the storage space of specimens. Once the essential lithologic features of a rock sample have been transferred to a slide, with or without auxiliary heavy mineral or paleontological sampling, the bulky sample itself may be stored away, leaving only an easily filed slide in the working laboratory. The serious map-maker may even take a small collection of critical slides into the field, using a small portable laboratory.

TECHNIQUE

The technique is simple: thin sections of any series of ordinary field samples of a particular age, cut at random, disclose a "certain look" that may distinguish it from a superficially similar group of another age. It may require expert research to say just what is the cause of any particular feature, say a certain characteristic form of oölite, but a glance may suffice to correlate two related specimens and to distinguish between two dissimilar ones. It is true that many rock types have a "look" that is almost universal or banal, in which case these are merely set aside, and one must concentrate on those possessing more individual, diagnostic characteristics.

The slides may be studied using the ordinary petrographic microscope, employing low, medium and high power objectives as the subject demands. Certain macroscopic features require a minimum enlargement or one may not

perceive "the wood for the trees." On the other hand certain important details of the fabric may require the highest magnification. For such purposes Professor Walter Bucher (personal communication) has recently been recommending the use of a binocular microscope with objectives up to 1200 times magnification.

The preparation of the slides presents little difficulty. Henson (1950, p. 216) recently touched on this question, and remarked: "Sections which are not required for mineralogical studies need not be cut to standard thickness, and if all unnecessary refinements, even cover slips, are eliminated, a good operator with mechanical equipment can make 20 sections or more per day." With mass production methods and suitable equipment, this number may be greatly increased.

Henson (1934) recommended that every field geologists should be equipped with a small portable laboratory for grinding his own sections—right on the job. On this basis the field man can often make improved correlations between otherwise indistinguishable rock types and may avoid the common error of lumping together similar lithologic types of distinct ages.

REFINEMENTS AND AUXILIARY TECHNIQUES

The simplest procedure is with random unorientated sections, but a number of refinements may be suggested that are appropriate in specific problems.

In carbonate rocks, where polarized light may not be required, a simplified technique is merely to cut and polish a single surface for examination under the binocular microscope. This, of course, is a limited technique, but may be a useful time-saver.

The use of the oriented section is an obvious refinement that has definite value with certain lithologic types. In core samples, where the top and bottom relationship is generally marked, it is very little extra trouble to cut the section normal to the stratification. Sedimentary features, such as the graded bedding of graywackes, will be immediately apparent; although the value of such structures for long-distance correlation may be limited, they should contribute significantly to the regional paleogeographic picture. It should also be borne in mind that the one thin section may be used for more purposes than direct stratigraphic correlation.

For carbonate rocks, or those with carbonate cements, one may adopt acid etching and, in the case of dolomites, possibly staining. However, staining generally adds little of diagnostic value. Since the mechanics of section-cutting automatically leaves two smoothly cut surfaces of rock as "waste," it does not add unduly to the labor to polish these lightly and apply etching and stain techniques, as recently summarized by Lamar (1950). Where these etched surfaces disclose additional information, photographs of them could be mounted for publication side-by-side with the thin section picture.

Like thin-section petrofabric study, etching has not received much attention in the past. Lamar (1950) remarked: "The etching of limestones with acids seems such an obvious procedure that a considerable literature might be expected on its application to calcareous rocks." But apparently this is not so; nevertheless Lamar provides us with an excellent introduction to the subject.

As a supplement to thin sections of carbonate rocks, etched surfaces may have great value in some cases; in others, very little. When they do show special features, it is partly because of the three-dimensional effect produced and by the larger area available for observation. Even less skill is required for their preparation, and examination requires only low power binocular microscope study. Finally, the etched surface may provide a direct comparison with the ordinary weathered surface of subaerial exposures.

Again, with etched carbonate rocks the use of transparent peels has been recommended for studying textures (Buehler, 1948). The technique was developed in paleontology by Darrah and others, a particularly simple and rapid peel technique being described by Sternberg and Belding (1942). It may be especially useful in dealing with soft carbonate sediments that are difficult to section. The heat generated by the sectioning process may cause aragonite to invert to calcite; in the study of the more recent sediments, this is a serious difficulty and may be avoided by use of the peel technique.

The logging of textural and mineralogical data observed by thin sections, etching, peels, etc. is of some significance, since the grouping and condensation of information is of great practical importance. A simple method of logging mineral particles was outlined by Banks (1950), and a modification of this scheme might be appropriate to the textural material. Mention is also made later in this paper of the work of Carozzi (1951) in reducing these data to a time/space curve.

AN EMPIRICAL CRITERION FOR CORRELATION

There is nothing new in the use of the macroscopic "look" of a sedimentary rock to an experienced geologist in aiding speedy field stratigraphic determinations (Krumbein and Sloss, 1951, p. 309-311). For example, there is a characteristic "Cretaceous look" that is possessed by chalks almost the world over; the danger of accepting such a criterion was early impressed upon the writer when he discovered there were almost identical-looking chalks in the Middle East ranging up through Eocene to Oligocene! Further, in the Precambrian the use of lithologic correlation, without collateral control, has resulted in appalling confusion. Nevertheless, when due precautions are observed, the "look" can be of great help in the field, and now the thin-section technique is offered as a refinement of the gross appraisal.

There also is nothing new in the technique of making thin sections, although in the past this has been a "luxury" service reserved for the study of some special feature, or a large microfossil. The normal sedimentary petrologic treatment, whereby the specimen is reduced to constituent grains, completely destroys many characteristic features developed during deposition. On the other hand, specific identification of the large microfossils often demands repeated sectioning and study by a highly skilled paleontologist. One can ultimately foresee, therefore, a considerable economy of effort in the adoption of this sedimentary petrofabric technique.

What is new, or relatively so, about the use of what Cuvillier calls the "micro-facies" is its adoption as an *empirical criterion for correlation*. As such it is now adopted as standard practice by many organizations with every

sample submitted for examination. This treatment requires extra labor, of course, but it is already bringing notable returns.

Henson (personal communication) says: "Those who have used this method habitually, feel that they cannot 'know' any rock, hard or soft, properly until they have seen it in thin section; and in addition to this generalization, it may be added that particular rock-sections may yield microscopic evidence of critical stratigraphic importance (e.g. determinable microfossils; recognizable derived material, etc.) which would escape observation by any other means."

Cuvillier (1951b) says that a recent oil survey of Aquitaine (France) "required the application of a system of stratigraphic correlation in which the micro-facies played a much more important part than microfauna. In fact, among the formations encountered both in outcrop and borehole, especially those consisting of hard rocks, calcareous, marno-calcareous, silicious, etc., correlations by microfaunas of foraminifera from washings are hardly practicable. Thousands of thin sections of these rocks, systematically sampled, have permitted, on the other hand, the realization of a detailed stratigraphic subdivision which embodies all the most characteristic micro-facies."

Microfossils may of course be *included* in these recognizable characteristics, for the field man may, without much prior knowledge of paleontology, correlate the "round flat ones" in this particular limestone, as against the "oblong spiney ones" of that limestone. They may be called forams A1, B3, etc. On return to base they may be submitted to an expert and properly identified, but the important thing is that the field man's mapping is correct, and if the Stratigraphic Code has been properly used, a note can be added without altering the map in any way stating that the "Gobblegut Limestone" is now identifiable on micropaleontological evidence as of "XYZ" age.

By an extension of the field work to a non-fossiliferous facies, it may be possible to pick up another (petrographical) characteristic of the rocks of this age. The calcareous facies may change to a sandstone, for example, and a new stratigraphic name (based on a local geographic feature) will have to be erected to identify it, but correlation may still be possible with the original "Gobblegut Limestone" and thence with the international age term.

PIONEER WORK

The study of sedimentary or depositional petrofabrics was, of course, pioneered by Bruno Sander and his students at Innsbruck (see, for example, Sander, 1948, 1950; also 1936, translation in English by Eleanora Knopf, 1951). This discussion is not concerned with the deformational fabric but rather with the primary, appositional fabric, which is related to initial depositional and diagenetic processes. To these must be added the environmental features, the micro-lithofacies and micro-biofacies, which the Sander school is now developing.

In this way a great deal has already been learned about *isolated* sediments. The use of such methods for correlation is relatively new.

Any perusal of the latest works on sedimentation show that the fabric or "look" of the rock type in thin section is now regarded as more important

than any other feature (see, for example, the magnificent illustrations in Pettijohn's book, 1949). The basic techniques of thin-section preparation may be found, of course, in any of the standard texts on sedimentary petrography, notably Krumbein and Pettijohn (1938), Milner (1940), Twenhofel and Tyler (1941), or briefly in LeRoy (1950).

At the Colorado School of Mines, LeRoy has used thin sections mounted on 2 x 2 inch photographic slides of the type employed for 35 mm projection; thus, not photographs but a thin section of the rock itself may be projected for training in the primary recognition of facies and formations. About the potential value of this approach LeRoy (1950) says: "Possible microscopic evidences that may be used include textures, structures, cementing minerals, detrital material, degree of crystallization, amount of crystallization, finer organic forms, and other morphologic criteria."

The probable use of thin-section study as a basis for the *local* stratigraphic correlation has long been realized by certain geologists, as evidenced in some prophetic remarks by Milner (1940): "The advent of core-samples of compact rocks in subsurface work has enhanced the possibility of differentiating between samples or correlating them by means of microscopical study of thin sections cut therefrom, more particularly in the case of argillaceous and calcareous rocks. . . . In many oilfields . . . where the sequence is made up of alternating limestone with shales etc., identification and differentiation of successive horizons may be a matter of considerable moment, though furnishing a problem in specific identification of no mean difficulty. It is here that the thin sections studied from a particular angle, may prove of considerable value."

In addition to carbonate and shaly rocks, as indicated by Milner, sandstones are also amenable to the thin-section approach. Krumbein and Pettijohn (1938) have devoted considerable space to demonstrating that grain size and shape can be dealt with effectively in this way, following prescribed methods and exercising certain precautions. A useful visual aid in percentage estimation is that issued by Folk (1951). However, although the use of terrigenous detrital rocks would appear to have regional value, they are as yet untried for really long-distance correlation.

Milner cautiously emphasized that these fabric studies might be effective for correlation "within a limited lateral distribution," and added "It is not for one moment contended that this line of inquiry *always* leads to precise conclusions or that the method is infallible; but thin section comparison of core-samples as of outcrop specimens is increasing in favour and this particular bias of what is only, after all, an intensive study of consolidated rocks according to well-established petrological principles, clearly has merits where no other means of correlating such types are available. . . . "

Nevertheless, almost nothing appears to have been published on the regional value of this stratigraphic technique until 1951, when Cuvillier briefly outlined its possibilities and presented an example.

The present writer is not certain who is responsible for the initial recognition of the method, but an early publication using it was issued by Udden and Waite (1927) who showed to Texas oil geologists the value of published

photomicrographs of the Bend and Ellenburger limestones. This bulletin may perhaps represent the first contribution devoted entirely to this sort of correlation. Before World War II the writer became acquainted with F.R.S. Henson and the late W. Kitchin of the Iraq Petroleum Company, who had been developing thin-section methods for many years.

Several other oil companies in the Middle East, France, and U.S.A. are known to be employing these techniques, some on a gigantic scale. Dr. Harold Wanless and his students at the University of Illinois are now applying them to the problem of late Paleozoic stratigraphy. One of those students (D. A. Robertson, 1951), in a work on Pennsylvanian sandstones from Kentucky, wrote: "Thin section study proved to be a fortunate choice of approach because any other method would have failed to disclose the true nature of these sandstones."

At a recent meeting of the Society of Economic Paleontologists and Mineralogists (St. Louis, April, 1954), P. L. and E. R. Applin demonstrated a fairly long-distance correlation based on micro-facies between Florida, Mexico and Texas. In this paper ("Lithologic and faunal characteristics of Lower Cretaceous and Jurassic? limestones of South Florida"), they used also paleontological material for dating, but the fabrics alone were most convincing.

THE AQUITAINE STANDARD

This valuable new discovery came to general recognition at the Third World Petroleum Congress held in The Hague in 1951, when Professor Cuvillier presented a summary of his oil company's work on the Mesozoic-Tertiary sequence of Aquitaine. At the same time he issued a book containing 178 microphotographs of every characteristic limestone formation in this thick rock column. On the basis of these illustrations, long-range correlations are already being made. Naturally, for close correlation, comparable geotectonic provinces must be chosen, but within this limitation, some remarkable facts emerge. Henson (personal communication) recently wrote: "Most of the Aquitaine microfacies, illustrated in Cuvillier's book, are so similar to their counterparts in the Middle East, that the one volume might serve, with some modification, for both regions.

INTERPRETATION OF SEDIMENTARY PETROFABRICS

It is not possible here to go into the question of the cause of the widespread reappearance of the characteristic "look" of the sedimentary fabric, but it appears to be akin to the cause of similar varves, "tele-connections" of which were shown by Baron de Geer (1940) to be correlatable with worldwide paleoclimatology, facies, eustasy, and tectonics. The cyclic or cyclothem type of sedimentation so extensively observed in the intra-cratonic basins of the world often show continuity of facies over tremendous distances. As Wanless and Shepard (1936) have suggested, the cause of such uniform changes is

no doubt connected with eustatic events, though not, in the opinion of the writer, necessarily glacially controlled, for there are many and varied causes for eustatic movements (Fairbridge, 1948). By this assumption such cyclic formations would have worldwide representatives, not in continuity, of course, but in favorable localities where climate, environment and tectonic framework are comparable.

One may select obvious examples of lithologic types which have widespread development in appropriate environments at certain restricted stages in Earth history. Related to the extreme eustatic oscillations of the Quaternary are two very distinctive lithologies: the oölites and the eolianites. Both are distinctly rare at other times, and so when this lithology does appear here and there in the geological column one may naturally seek an analogous genesis related to major eustatic changes. Researches into the eolianites suggest that there were special conditions pertaining to the broader continental shelves during the late Pleistocene in the warmer latitudes that makes them almost unique (Fairbridge, 1950; Fairbridge and Teichert, 1953). This is an extreme case, but it serves to illustrate the principle.

In this connection one might draw attention to the suggestive work of Carozzi (1951) in Switzerland, who has devised a method of illustrating by curves the variations in time and space of the main mineral and organic components (i.e. the micro-facies) of a formation. The relationship to ecotope and tectonics is indicated. This treatment has particular value in cyclic sedimentation (see also Brückner, 1953).

It would appear that Carozzi's technique might be further utilized for micro-facies correlation, the space (time) mineral curve taking the place of the thin section; it need hardly be stressed, however, that the transfer of the visual data observed on the slide to the mathematical form of the curve is a slow and laborious procedure. The great advantage of the direct visual comparison is its speed of operation.

The introduction of the time element, however, has merit, for it emphasizes the over-riding control in all sedimentation, that is, the progressive and irreversible nature of the process. This is the ultimate explanation of why, for example, a certain sediment in the Cretaceous will generally be distinguishable from a closely analogous equivalent in the Permian.

Both the biota and sediment-source are involved in evolutionary developments. Thus both biofacies and lithofacies must progressively evolve with time in certain minor characteristics, reflecting the long-term evolution of their provenance material. Furthermore there are irreversible elements of universal scope: the chemistry of the sea water, and the geochemical and geotectonic development of the Earth's crust, over and above the local development of the tectofacies.

From the above discussions it is apparent that the carbonates are the major lithologic type on which fabric correlation has so far been tested. Cherty and phosphatic rocks may also be sensitive indicators. Caution has already been urged with long-range attempts on sands and shales, for these

terrigenous sediments are essentially related to their own region of source materials; they may well be lightly characterized by a quite minor element of more universal significance, but this remains to be proven. If one accepts certain basic geotectonic rhythms, even if not adopting the absolute universality of Stille's "phase plan," it would seem inevitable that terrigenous and volcanic sediments should closely reflect contemporary tectonism, and an element of evolutionary, irreversible nature is superimposed by those rhythms.

The striking initial success with the carbonates in fabric correlation is related primarily to the above-mentioned biologic evolution, for most limestones are becoming recognized today as related in some way to organic processes. Furthermore, both this biotic control and the delicate geochemical balance of calcium and magnesium carbonates in sea water (again, in part, biochemical) tend to have universal features for any one stage in Earth history.

Since these "universal" features may often be bound up with climatic events, some caution may well be exercised in making long-distance north-south correlations. Success has already been noted with east-west connections, that is, *within* the same major climatic belts, but it seems inevitable that certain features will not be traceable directly *across* these important biogeographic frontiers. On the other hand, paleoclimatologists generally regard the present time as one of rather extreme climates, so that this restriction may be less effective in the more equable periods.

In any discussion of carbonates, it is essential that the multiple workings of diagenesis should not be forgotten. The inversion of aragonite to calcite, secondary cementation, dolomitization, and reverse effects may all play a role in blurring the primary characteristics. They may render the originally similar sediments now superficially quite unlike. "Superficially" is used deliberately, because diagenetic alteration is often highly selective, original ratios and proportions may be altered, but some characteristic forms may survive.

Finally, one may turn to the crowning question. Following the doctrine of Lyell, the marine geologist must now determine the little diagnostic characteristics that distinguish the sediments of today from equivalent facies of the past. What are these subtle features?

RESTRICTIONS AND PRECISION

It should not be imagined for one moment that the micro-facies technique offers a universal panacea for correlation problems. Since neritic environments, with carbonate and other shallow-water sediments, are the most easily affected by eustatic and climatic changes, it is here that the best correlation data are to be found. In bathyal environments, on the other hand, a eustatic change of a few feet will have no immediate effect on either bio- or lithofacies.

Likewise, universal changes will be most marked in regions of relatively slow and undisturbed sedimentation, thus in the parageosynclines (of Stille, 1935), i.e. the semi-stable cratonic basins. For example, marine paraliageosynclines, autogeosynclines, and exogeosynclines are in marine connection the world over and at the same time are the least liable of sedimentary basins to tectonic disruption.

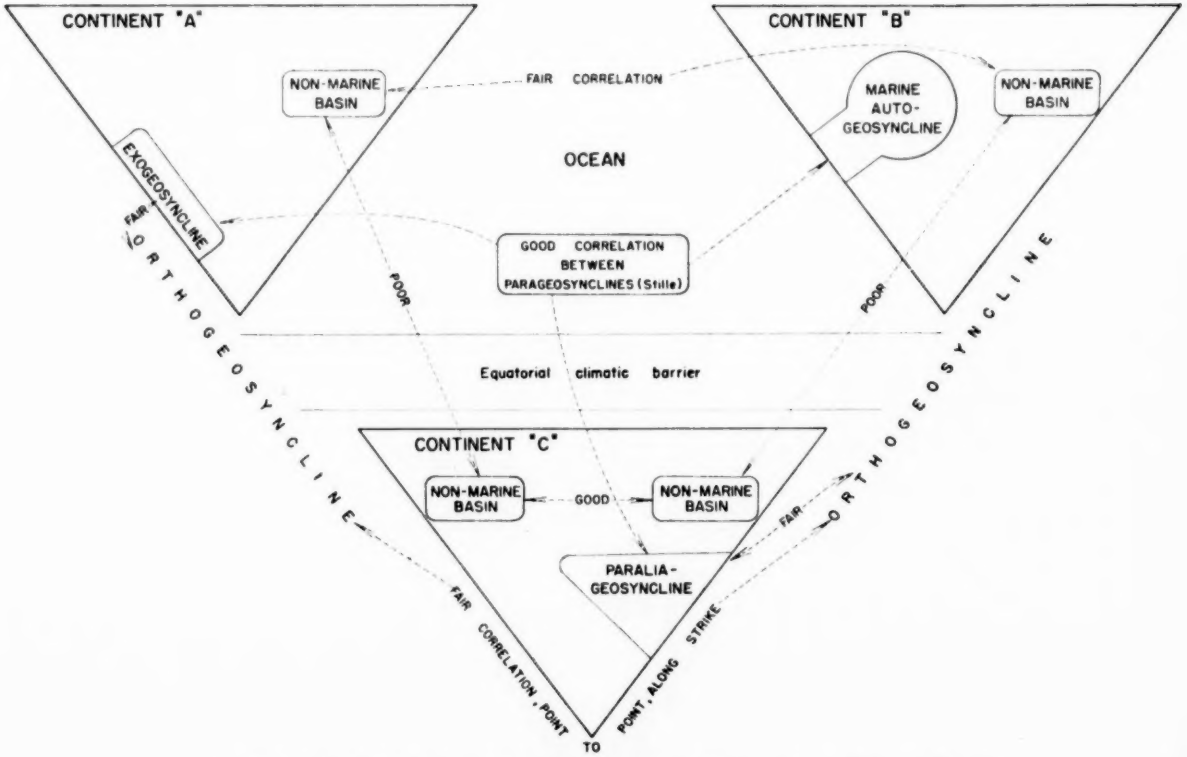

Fig. 1. Diagram to illustrate the relative value of sedimentary correlation by microfacies, on an intercontinental basis, for varying geotectonic environments (using the geosynclinal terminology of Stille and Marshall Kay).

In contrast the orthogeosynclines are constantly suffering revived tectonism, their sediments (typified by the graywacke suite) are so rapidly accumulating that they tend to mask or destroy traces of contemporary biofacies and subtle traces of less local significance. Correlation between such basins with one another along the strike is often assisted by tectofacies, but across, into the parageosynclines, the correlation is likely to be carried on the thin carbonate or littoral type intercallations that sometimes occur. In short it is difficult to conceive of the graywacke regularly becoming useful for the application of this technique. Thus it may never be of great value in the orthogeosynclines, and more especially the eugeosynclines of the Precambrian.

By the same token, continental sediments (from non-marine basins) would also appear to be generally unsuitable for correlation on an intercontinental level. Although similar climatic conditions may affect similar latitudes (see the success of de Geer's varve correlation), a correlation across the equatorial climatic barrier would appear to be most hazardous. In any case, continental environments are deprived of the unifying effects of the marine continuum, of eustatic controls and of biofacies.

In summary, it would seem that the technique should be applied initially to parageosynclinal regions only and even then to relatively short "hops" within similar climatic belts.

Then comes the question of precision. Just how fine a correlation may be expected? In Aquitaine, the stratigraphy was scaled down to formations and members (substages). In less favorable environments, particularly those from deeper water or with a dominant clastic fraction, it may be that we shall have to be content with a series or even sub-period designation.

The greatest danger seems to lie in the well-known cyclic repetition of like facies within each diastrophic sequence. In finer cyclic repetitions it is obviously easier to select suitable markers and set aside the more banal sediment types. One may think here of the residual quartz sands that constantly reappear in certain sequences and all seem to have the same parents, the same degree of rounding and the same cementing material!

It would seem therefore that the degree of precision that may be obtained will be controlled largely by the basic characterization of the sediments concerned. A monotonous sequence of ferrugenous clastics such as an Alpine "flysch" or a graywacke can hardly be expected to disclose much more character in thin section than it does in the hand. Yet it should be worth trying. One does not know till one has looked.

WORLD STANDARD SERIES

Naturally a suite of stratigraphic samples from one region alone cannot be used as a sole world standard and further sets are needed for all ages and from all parts of the Earth. A remarkable opportunity here seems readily available for stratigraphers the world over to set up local standards to help solve awkward correlation problems. Ultimately, when adequate standards are available, the micro-facies technique may help in deciphering structural

conditions. The need is now for interested stratigraphers and sedimentary petrologists to accumulate data on numerous local sections, and to publish regional standards. It would seem an ideal technique for Ph.D. candidates, offering problems as small or large as time and interest permit.

In order to encourage the erection of regional standards, the Dutch publishing firm of E. J. Brill in Leiden, which published the Third World Petroleum Congress reports and Cuvillier's little book, has undertaken to print a series of similar illustrated handbooks, and Dr. H. M. E. Schürmann, the well-known Dutch oil geologist, has agreed to act as general editor.

Further inquiries could be addressed to Dr. H. M. E. Schürmann, Waalsdorperweg 149, The Hague, Holland; or Dr. F. R. S. Henson, Iraq Petroleum Company, 214 Oxford Street, London W. 1.; or Dr. H. R. Wanless, Department of Geology, University of Illinois, Urbana, Illinois, U.S.A.; or Dr. R. W. Fairbridge, University of Western Australia, Nedlands, W. A., Australia.

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DISCUSSION

NOTES ON CRATER MOUND IN ANSWER TO SOME POINTS RAISED BY H. H. NININGER

DORSEY HAGER

In his article entitled "Impactite Slag at Barringer Crater," in this Journal (1954, v. 252, p. 277-290), H. H. Nininger (p. 288) makes some reference to a paper of mine published in the *Bulletin of the American Association of Petroleum Geologists*, April, 1953. I think Nininger has entirely missed the significance of the geologic observations as he dismisses the geologic features quite cavalierly. On page 289 he mentions a reference to graben 60 miles distant and assumes that I call the crater a graben on that basis. The crater speaks for itself. Both the northwest and the southeast ends are definitely graben and are easily recognized as part of a fallen arched feature.

The occurrence of graben and sink holes in the area is well recognized. Crater Mound may very well be just another sink only of larger size than most, only here meteoritic material is present. It is possible that this is a combination of a sink hole and a dome over an evaporite section or possibly a dome raised by an igneous mass which did not reach the surface but did allow subterranean solution to occur. These possibilities should be taken into consideration.

There are six marked faults, one small one, not thirteen (see map), as stated by Nininger. Several slight displacements (small slips) in upper beds do not carry downward in the crater walls and are purely surficial features.

Again Nininger questions the presence of evaporite beds. In one of several geologic hypotheses I postulate the possible presence of evaporite beds in the underlying Supai formation at depths of 2000 feet, more or less. Such evaporite beds were found in several tests for gas and oil made 35 miles southeast of the crater. Also evaporite beds occur in the Supai formation south of the crater below the Mogollon rim. Nininger states that the presence of such beds at Crater Mound is disproved by water wells drilled by ranchers around the crater. He fails to note that such water wells are all in the Coconino sandstone which overlies the Supai beds. The Coconino is the main aquifer in that part of Arizona and is exposed in the walls of the crater. The Coconino sandstone does not carry evaporite beds and had no place in my argument. However, Nininger fails to observe that graben and sink holes are also present where evaporite beds are lacking especially further northwest toward the Grand Canyon. One of my hypotheses takes this into consideration.

Nininger also fails to consider the occurrence of the crater on the axis of Sunshine Nose, a marked feature in the area. The direction of the axis of Crater Mound is the same as the axis of Sunshine Nose.

The original height of the dome around 800 to 1000 feet is not out of line for such a feature. The well-known Upheaval Dome in northwest San Juan County, Utah has an uplift of nearly 1800 feet. That feature rises from a ring syncline as does Crater Mound. While there is no sink in the center, the general geologic features are otherwise quite similar and of similar order of magnitude—a rise of 1800 feet or more from the ring syncline to the top of the dome in 1¼ miles as compared to 800 to 1000 feet for Crater Mound in a distance of ½ mile. The Brady Creek, Tennessee, crypto-volcano is another feature of similar magnitude.

Nininger makes the statement that I assert the rock flour is mainly just sand. Buddhue's careful analysis (1948) shows sizes of 34.01% medium; 37.73% fine sand; 12.79% very fine sand; and 14.37% under 200 mesh, which comprises 7.85% under 400 mesh. The 200 minus is the so-called "flour sand"—a powdery sand. Some of the thin spine-like splinters in the sand are fractured. Similar sands in the walls of the crater do not show such fracturing. Geologic processes, weathering, and release of tension from folding could cause such fracturing. It seems most likely, however, to be a weathering process. At other places than at Crater Mound fine flour-like Coconino sands and flour-like sands in the Kaibab occur. I disagree with Nininger on the character of the sands in the Kaibab limestone, also some of the Coconino sandstone. Under the microscope fine sand slivers are common in the arenaceous Kaibab beds, and parts of the Coconino sandstone carry many fine slivers generally unbroken where the beds are in place.

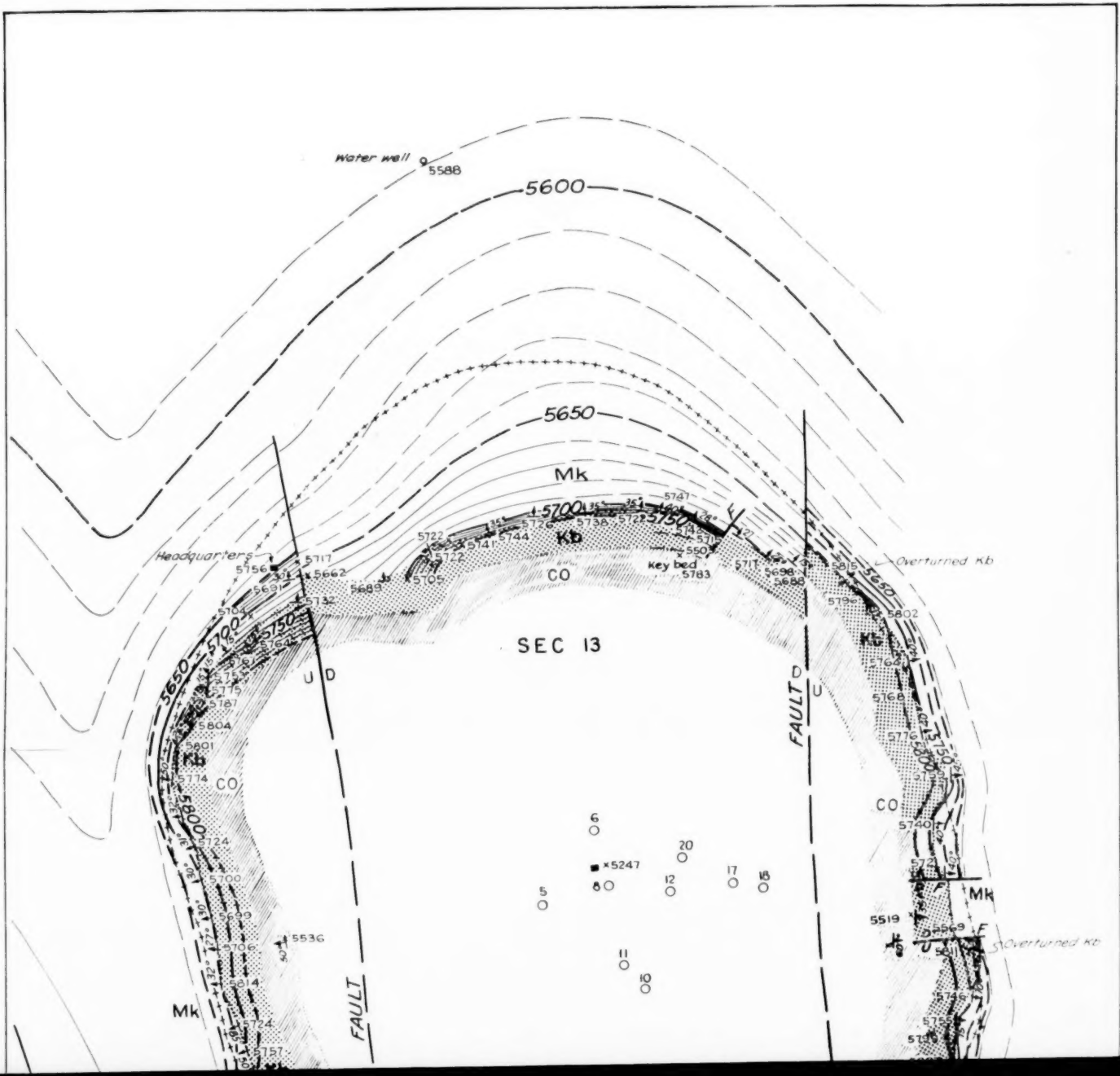
Nininger seems to think that the only way sands can be shattered or broken is due to impact, but weathering and folding processes also cause fracturing. The fine slivers found in loose sands would be easily broken. Where found in the walls the sands are not fractured. Also, the material in the walls shows no effects of high temperatures.

In paragraph 5 Nininger takes issue with the fan-like distribution of the meteorites that I show in my paper. That distribution is more logical than the radial pattern set by Barringer, Sr. Under Barringer's hypothesis the meteorite came from the northwest which doesn't apply as well as the meteorite having come in from the northeast. The northwest direction is pure speculation with no supporting evidence, whereas a northeast direction is more logical.

Nininger says in paragraph 6 that I didn't note the impactites, but I had read Nininger's earlier paper and the surficial occurrence of the material on or near the top of the bedded deposits convinced me that his own evidence showed a fall later than the early deposition of the bedded sands around the rim.

Also, Barringer's accounts of meteoritic fragments (1909) bear out my interpretation. He says:

> "It is interesting that so far no piece of the ordinary unoxidizable Canyon Diablo iron has yet been found deeply embedded in the silica on the slopes of the mountain, *but always on top of it, that is on or very near the surface, where many hundreds of specimens have been found. I have no completely satisfactory explanation to offer for this fact.*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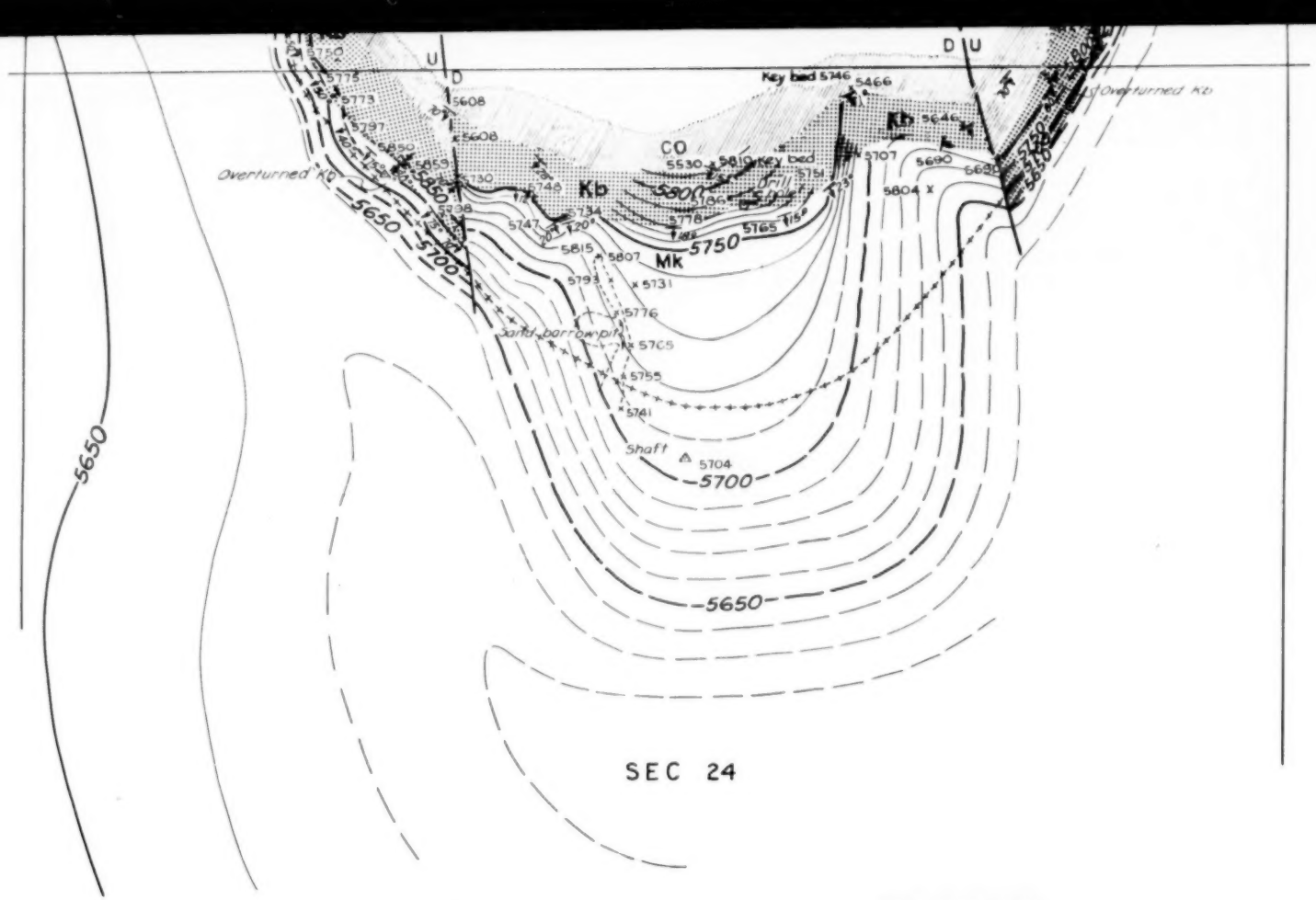

GEOLOGIC AND STRUCTURAL MAP
OF
CRATER MOUND
SEC. 13 & 24 T. 19 N. R. 12½ E
ARIZONA
GEOLOGY BY DORSEY HAGER

0 400' 800' 1200 FEET

Contour interval 10 Feet
Drawn on top of the Kaibab L.S.
Datum-Mean Sea Level
1951

EXPLANATION

Mk	MOENKOPI	+++++	PRIMARY WALL (?)
Kb	KAIBAB LS	F	FAULT
Co	COCONINO	x 5827	ELEVATION POINT
	STRIKE & DIP OF BEDS		CONTOUR LINE
	OVERTURNED		APPROX. CONTOURS

Fig. 1

> Again one of these large iron meteorites, with no shale surrounding it, was found slightly embedded, but with a point protruding, in the silica and rock fragments on the northeast slope of the mountain, and almost immediately beneath it within a few feet, there was found a large shale ball meteorite with a solid iron center. It is certain that neither had been moved appreciably since they came to rest in the silica and ejected rock fragments. Possibly these large, deeply pitted, and many of the small meteorites, both of which we know as ordinary Canyon Diablo siderites, *were individual meteorites trailing behind the cluster.*"
>
> (Italics by Dorsey Hager.)

I do not claim that a geologic hypothesis is final, but the evidence for one of several geologic hypotheses of origin seems far stronger than for meteoritic origin. Certainly a meteorite or a meteoritic shower fell in the near vicinity, but the crater was already present and not formed by the meteoritic fall.

A great deal more work must be done on the crater by meteoriticists and by geologists before the meteoritic hypothesis becomes even a theory. The same is true for the geologic hypotheses. Nininger recognizes that the meteoriticists have to answer a number of questions.

The solution of this problem can best be settled by a series of drill holes deep enough to penetrate a datum bed within the crater, on the rim, and outside the crater. These holes should determine whether or not the feature is a geologic fold or an uplift due to impact.

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REPLY

H. H. NININGER

In my recent paper on impactite in this Journal I submitted a brief evaluation of some of the salient points in a paper by Dorsey Hager published in the *Bulletin of the American Association of Petroleum Geologists*, April 1953. In the present issue of this Journal Mr. Hager replies to my criticism with certain statements which seem to require further elaboration of some of my objections to his conclusions. The Journal has kindly offered me the courtesy of further clarifying these points.

I criticized his attempt to picture the crater as a graben by pointing out that "graben are commonplace in the area," then citing graben some 60 miles to the northwest, and by assuming that two "fallen arch structures" in opposite sectors of the crater rim are connected under the crater floor. He makes

the statement that these rim faults "are not radial as has been stated in earlier works" but he submits no evidence in support of this claim nor any proof that they are connected through or under the crater floor. In his reply to my objection to citing graben 60 miles away as evidence of the graben nature of the crater, Hager replies that the crater speaks for itself. But as I have cited above it *speaks* only if one makes two bold and unsupported assumptions.

If Hager wishes to make the term graben apply to any and all fallen arched structures, then one might agree that we have graben in both the northern and southern sectors of the crater rim where apparently the sedimentation beds were momentarily lifted and dropped as the meteorite ploughed into the Earth and exploded. But I object to considering the crater pit as a graben until his inferred faults through its floor are proven to exist or at least convincing evidence is cited in support of their existence.

Objections are raised to my refusing to accept Hager's postulated evaporite beds in the Supai formation. The only support cited for this postulate was the existence of evaporites in the Supai 35 miles to the southeast. Extensive exposures of this formation in Oak Creek Canyon 30 miles to the west fail to indicate evaporite beds. Thus this postulate seems purely arbitrary.

Furthermore, I wish to clarify my objection to Hager's selection of what he considers evidence in favor of a geological rather than an impact origin for the crater. His paper begins with a description of a geological and topographical area 120 by 20 miles in extent that is marked with graben and sinkholes and within which the crater lies. He states that the crater "may very well be just another sink only of larger size than most."

On paper his presentation becomes very convincing to those who are not familiar with the area. But in contrast to that presentation I wish to emphasize the following known *facts*.

No sinkhole or graben in this area can be remotely compared with the crater as to (1) its general appearance, (2) the symmetry and uplifted form of its walls, (3) the blanket of broken-up rubble derived from the three upper formations of the area, (4) the presence in its pit and among the rubble on the rim of millions of tons of rock flour described by Barringer and studied by many scientists, (5) the scattered deposit of large boulders, from the normally buried sediments, found on various sides of the pit out to distances of more than a mile in locations remote from any visible trace of water courses, (6) the surrounding deposit of some 40,000 recovered meteorite fragments, (7) the presence of meteoritic material mingled with the fill in the pit and in the rubble of the rim, (8) the surrounding deposit of several thousand tons of nickeliferous particles in the form of metallic spheroids, (9) the presence in the rubble on the rim of millions of lumps of fused country rock in the form of slaggy bombs and droplets recently described by me as *impactite*.

All the above-cited conditions are well established in connection with the Arizona crater. Such combinations of conditions are very rare on the Earth, and so far the only other locations in which they have been found are marked by craters closely resembling the Arizona crater except as to size and apparent age.

In paragraph 5 Hager criticizes me for failing "to consider the occurrence of the crater on the axis of Sunshine Nose, a marked feature of the area." I have not failed to consider this fact but have placed quite a different valuation on it than does Hager. The structure was first brought to my attention in an unpublished report by Hugh M. Roberts written in 1919, a copy of which is in my file. One reason that I attach little importance to the association of the crater with this structure is that there are thousands of such structures on the land surface of the Earth, and the coincidental association of any feature with one of them does not require explanation involving generic relationship. Hager himself (1953) says that Sunshine Nose "is but one of several similar features which occur northward to the Kaibab plateau. Low doming occurs on those other features; none, however, as pronounced as at Crater Mound."

It is only fair to point out that the Sunshine Nose is much more conspicuous on the Hager map (1953, fig. 3) than it is in the field. According to his statements in the last two paragraphs of page 824 of his original paper every line on that map represents "inferred conditions" except that which outlines the crater pit. Indeed, as one studies the maps in figures 2, 3, 4 and 7 especially, one wonders why he has been willing to stress so heavily "inferred conditions" while giving so little emphasis to such outstanding *facts* as the nine which I have cited above.

One has difficulty in following the Hager logic. On the one hand he considers as very significant the simple fact that the crater lies on the axis of an anticline, of which there are literally thousands. Yet he sees no necessary significance in the association of a startingly distinctive collared pit with some 40,000 heavy nickel-iron meteorites, billions of metallic spheroids also of nickel-iron, millions of slaggy bombs containing more millions of nickel-iron particles and, except for these particles, showing approximately the same composition as the sediments in which the crater appears. This pit is unlike known volcanoes. It is unlike known sinkholes. It lacks certain essential features of steam or gas blowouts. There are a few other rimmed pits similar in structure, and in each case where they have been adequately explored meteorites have been found associated. All these facts are regarded as coincidental by Hager and are given very small consideration in his paper, and some are not even mentioned.

Hager insists that the rock flour is merely sand. He cites Buddhue's paper (1948). Here Buddhue was dealing with rock flour only incidentally. He was analyzing a sample of sandstone in the crater wall that had been "crushed but not dispersed." In this he found a small percentage that could not be distinguished from the rock flour. Indeed it is evident that there was no difference except that the rock flour had been dispersed. In fact, one may find at the crater sandstone in all stages from that which is normal, being composed of worn sand grains held together by a binding medium, to that in which all of the grains are either crushed or fused, described by Barringer and Mallet as Variety A of metamorphosed sandstone, or to the more advanced stage of metamorphism in which the effects of heat are more marked and the granular nature is lost in complete fusion.

The inference on the part of Hager (paragraph 8) that I think the only way sand can be shattered is by impact is, of course, erroneous. Certainly folding can cause fracturing of sand grains but not to an extent that would yield 50 million tons in such a limited area as the walls of the crater encompass. A layer 100 feet thick lining the Coconino portion of the crater wall would just about yield the required tonnage to account for what is now present, and in all probability a greater tonnage has been removed from the crater environs during our modest estimate of 50 thousand years. I seriously doubt that Hager wishes to claim that such a quantity has been produced by folding and weathering in the small area. But *if* these factors *have* been responsible then why do we not find comparable deposits of rock flour at other sites? I have examined a dozen large sinks 30 miles south of the crater where the entire section of the Kaibab is exposed. Not even a small sample of rock flour was in evidence.

In Hager's paper the Kaibab arenaceous limestone is assigned as the principal source of the rock flour. At least a hundred times as great exposures of this formation are to be found in nearby canyons but none of them yield even a sample of the kind of rock flour that is found at the crater.

Now in closing let me say that Hager and I agree on at least one point, namely, that there should be a great deal more work done at the crater. During the past eight years I have spent a considerable portion of my time in field or laboratory working on problems related to this great crater. During those years I have discovered the following facts that had been overlooked:

1. A radiate distribution of meteorite fragments.
2. A zonal distribution of meteorite fragments as to size.
3. A zonal distribution of meteorite fragments as to heat effects.
4. The presence among the fragments of a small percentage which differ from the majority in both structure and composition.
5. The presence around the crater of an enormous tonnage of metallic spheroids composed of the meteoritic metal, but exceptionally rich in Ni, Co, and Pt.
6. The presence of a considerable tonnage of slug-like particles comparable in size with the spheroids, but having the same composition as the well-known Canyon Diablo irons.
7. An abundance of impactite slag.

My most important conclusion from these years of work is that the scientific study of this crater remains, for the most part, to be done in the future.

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ESSAY REVIEW

Contribution a l'étude du Cambrien inférieur et du Précambrien III de l'Antiatlas Moracain; by PIERRE HUPE. *Introduction stratigraphique*; by GEORGES CHOUBERT. Notes et Memoirs de la Service Géologique du Maroc No. 103. P. 402; 99 figs., 24 pls. Rabat, Morocco, 1952.—This fine inclusive work merits the attention of every serious student of Cambrian paleontology and stratigraphy. It excellently describes one of the world's most completely developed Lower Cambrian faunal sequences. A brief stratigraphic introduction by Choubert is followed by an extensive paleontologic part by Hupé, also author of the trilobite portion of the *Traité de Paléontologie*. Because the strata contain faunas of the North Atlantic province, the old American term, Georgian series, is used. It is applied to the upper part of an exceptionally thick (16,000 feet) sequence of sedimentary rock in the western Antiatlas Mountains.

The strata are transgressive southeastward, thinning rapidly to less than 500 feet in Jebel Sarhro. Their maximum development is as follows:

ACADIAN	Marine sequence	3000 ft.	*Paradoxides* faunas
	Terminal sandstone	500 ft.	protolenid trilobites
	Shale complex	1200 ft.	olenellid-redlichid trilobites
GEORGIAN	Shale-limestone	1400 ft.	olenellid-redlichid trilobites
sensu stricto	Upper limestone (calcaires supérieurs)	1300 ft.	archaeocyathids and stromatolites
(second cycle)	Regressive maroon beds (lie de vin schistes)	2200 ft.	stromatolites and archaeocyathids
INFRACAMBRIAN	Lower limestone (calcaires inférieurs)	9000 ft.	stromatolites
(first cycle)			
— — — — —	unconformity — — — — —		
PRECAMBRIAN III	very thick disturbed continental and volcanic terrane		stromatolites

Eight trilobite zones in the higher part of the upper Georgian cycle are distinguished by Hupé from numerous early collections and his own later field collecting. An extensive fauna of 85 species is listed, attesting to a considerable amount of effort on the part of the describer. The lowest zone contains both olenellid and primitive redlichid trilobites indicating, as do all succeeding zones, a mingling of North Atlantic and Asiatic faunas, the former represented by eodiscids, olenellids, protolenids, and ellipsocephalids, and the latter by the superfamily Redlichoidea. The discovery of the Asiatic redlichids in Morocco links the Spanish and Dead Sea occurrences of this fauna (Richter and Richter, 1940, 1941a, 1941b), and better documents the extent of the early Paleozoic Tethyan geosyncline. Both olenellids and primitive redlichids are present in all zones except the upper two where they are replaced by protolenid trilobites. The base of the Middle Cambrian is placed at the lowest occurrence of *Paradoxides* which Hupé considers a redlichid descendant.

Proper placement of the base of the Cambrian is discussed. In the Moroccan strata stromatolitic algae (*Collenia*) first occur in Précambrien III and in the calcaires inférieurs. Archaeocyathids appear in the maroon beds (lie de vin schistes) and are found with new and distinctive species of *Collenia* throughout the calcaires supérieurs. Trilobites make their first appearance hundreds of feet higher in the shale and limestone unit of the second Georgian

cycle. Hupé argues against using olenellid trilobites as definitive for the base of the Cambrian since it can be demonstrated that their lowest occurrence is not everywhere of the same age. Within the Moroccan province of sedimentation their earliest occurrence coincides with the lowest development of transgressive argillaceous strata above the calcaires supérieurs. The oldest olenellids of the *Holmia* zone in England and Norway compare well with those found in the Moroccan zones V and VI. Even the conjectured oldest olenellid in North America (*Nevadia* Walcott) is much less primitive than the trilobites in Hupé's lowest zones. Indeed, Hupé suggests that the presence of any sort of fossils is not the best criterion for drawing the base of the Cambrian. The accidents of fossil collecting in very ancient strata may improperly place large sections of Lower Cambrian strata in the Precambrian if mere presence of organisms is the criterion. The ability of evolving organisms to develop hard parts may have been dependent on local climate and latitude. He believes that the warm climate, indicated by the rocks considered, encouraged in Morocco an unusually early development of calcareous tests on all organisms, seemingly in chronological order corresponding with their biologic rank, i.e. first algae, then pleospongids, and later higher invertebrates. Actually, the boundary is drawn in the Moroccan sequence with a consideration of sedimentary cycles, in much the same manner as P. B. King (1949) proposed for the southern Appalachians. The base of the Infracambrian (calcaires inférieurs) is drawn just above a major unconformity, but the base of the Lower Cambrian per se (Georgian sensu stricto) is placed above these strata in beds just below the second cycle of deposition. The basal Georgian sensu stricto contains the first archaeocyathids, but trilobites occur much higher in the sequence.

The descriptive paleontology is preceded by a small section on trilobite terminology. Classification follows that given by Hupé in the *Traité de Paléontologie*. The excellent sketches which accompany the descriptions are one of the work's finest points. Generous use of explanatory paragraphs concerning generic and family concepts combined with the sketches clarify the taxonomic principles employed. A detailed discussion of the olenellids with a complete nomenclature of their parts is most helpful. Five new genera of olenellid trilobites are added and seven subfamilies created. A conical or truncate-conical glabella and abundant prothoracic segments are believed to be primitive characteristics in the olenellids. The important new genus *Fallotaspis* is discussed below.

Hupé follows Henningsmoen in his concept of a large superfamily, Redlichoidea. This he subdivides into 14 families, grouped into (1) the more typical redlichids (confined to the Lower Cambrian) and (2) seemingly derived families that resemble some of the ptychoparoids and corynexochoids. Our present knowledge is perhaps inadequate to place properly several of the families of group 2.

A further important paleontologic contribution concerns the general evolution of Lower Cambrian trilobites. The primitive trilobites from the Moroccan Georgian show as many as three pre-oral segments (antennule, preantennule, and X segment). These are well illustrated, and it is demonstrated

how their pleural portions form, in some species, long trifold or bifold ocular ridges, and their axial portions a parafrontal band anterior to the glabella and/or additional glabellar lobes. Great similarity in structure and evolutionary trends is found between the olenellids and redlichids. The glabellar structure and facial sutures are compared, the olenellids, with retrodivergent facial sutures, being considered a derivative off the main trunk of trilobite evolution which included typical redlichids. The back-bending of the olenellid preocular facial suture (following Raw's theory) seems demonstrated by a species of Hupé's new genus *Fallotaspis*. In this form, clear vestiges of the suture may be seen with the free cheek almost completely ankylosed, much resembling later trilobites with this condition as described by Ross and Rasetti. An interesting discussion is given (though as yet poorly documented with larval forms) concerning the origin and ontogeny of the cranidial spines. An important discovery is that not all olenellids have a hypostome attached to the rostrum, e.g. *Fallotaspis*. The obliteration of the hypostomal suture in the olenellid group may therefore be secondary. Comparisons of the thorax and post-thoracic segments of olenellids and redlichids are discussed. In sum it is believed that the redlichid trunk gave rise to olenellids in the Precambrian since both groups are represented in the Moroccan strata by primitive but well-differentiated forms.

An addition to the main work, entitled "Concerning the *problematica* from Precambrian III," is particularly interesting because it offers information on the origin of the alleged giant arthropod remains (*Beltina* and *Protadelaidea*) found in late Precambrian strata in several parts of the world. The article is also replete with sketches and photographs of these abundant, nodular, segment-like forms that occur on bedding planes in the Sarhro region. Possible origin as moulds of arthropod segments are rejected because of general asymmetry and lack of consistent patterns. About 20 types are described. The explanation offered is that these forms were once dried mud scales or curls that formed in a thin layer over a sand surface. The scales were rolled into various shapes as the sun dried them and were later buried, perhaps subaerially, with sand.

Hupé does not discuss the other fossils found with the numerous trilobites, and any consideration of paleoecology is omitted. We would like to know more about the archaeocyathid reefs; the prevalence of trilobites only in argillaceous strata; how abundant are the inarticulate brachiopods; and whether any gastropods were collected. Notwithstanding, a reference work of major importance has been presented which will be of extreme value to American paleontologists when the oldest Cambrian strata in our geosynclines are investigated systematically.

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JAMES LEE WILSON

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VOL. 252 No. 11, 1954

American Journal of Science

NOVEMBER 1954

CONTENTS

FABRIC ANALYSIS OF SOME GREEK MARBLES AND ITS APPLICATIONS TO ARCHEOLOGY ..... *L. E. Weiss* 641

RELATIONS OF THE PROPERTIES OF WISCONSIN LOESS TO TOPOGRAPHY IN WESTERN IOWA ..... *Robert V. Ruhe* 663

PROBABLE OCCURRENCE OF OLIGOCENE ON SAIPAN ..... *Ruth Todd, P. E. Cloud, Jr., Doris Low, and R. G. Schmidt* 673

STRATIGRAPHIC CORRELATION BY MICRO-FACIES ..... *Rhodes W. Fairbridge* 683

DISCUSSION

NOTES ON CRATER MOUND IN ANSWER TO SOME POINTS RAISED BY H. H. NININGER ..... *Dorsey Hager* 695

REPLY ..... *H. H. Nininger* 697

ESSAY REVIEW

Contribution a l'étude du Cambrien inférieur et du Précambrien III de l'Antiatlas Morocain; by PIERRE HUPÉ. Introduction stratigraphique; by GEORGES CHOUBERT *James Lee Wilson* 701

PUBLICATIONS RECENTLY RECEIVED 704